Exotic nanophotonics with subwavelength high-index disks

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***Abstract*- High-index dielectric disks with subwavelength dimensions seem relatively simple electromagnetic structures. However, they can give rise to exotic phenomena in nanophotonics. Here we show recent findings that show that high-index disks can be used to manipulate light in subwavelength dimensions as a result of Mie and Fabry-Perot resonances. We also propose that such disks can be used for new applications in photonic integrated circuits (PICs) using silicon technology.**

I. Introduction

A disk formed by a material with a high index of refraction ($n > 3$) is one of the simpler structures in photonics. For large values of the radius r (in terms of wavelengths), high-index disks exhibit whispering gallery modes (WGMs) [1] arising from total internal reflection at the inner disk boundaries which can lead to high-Q optical resonances [2]. This property can be used, amongst other applications, to build highly-sensitive label-free biosensors integrated on a silicon chip [3]. In the quest towards extreme miniaturization of photonic nanosystems, it would be highly desirable to reduce the size of the disk as much as possible, even reaching the subwavelength scale. When $r < \lambda$, being λ the wavelength in vacuum, the disk does not longer support WGMs but displays multipolar Mie resonances instead. Although such resonances do not have a Q-factor as high as in the case of large disks, they exhibit other interesting features that have led to the emergence of the field known as high-index nanophotonics [4].

Here, we review recent results showing how subwavelength-size silicon disks fabricated using conventional technology can lead to new phenomena and applications that can be highly interesting to improve PICs.

II. On-chip Anapole Resonances

As mentioned above, electrically small high-index disks support a set of multipolar resonances. In the case of a thin (thickness $t << r$) high-index disk with subwavelength dimension, the main multipolar contributions will be the electric and toroidal dipoles. Notably, these dipoles possess the same far-field radiation pattern. Under certain conditions, the electric and toroidal dipoles are excited with the same amplitude but out-of-phase, meaning that the far-field scattering is completely suppressed because of destructive interference. The resulting radiationless state is called an anapole [5] and, besides showing no scattering, has the remarkable property of enhancing the local fields inside the disk, which has been used to boost nonlinear optical interactions [6].

Previous works on anapoles in high-index disks have made use of excitation parallel to the disk axis. However, in order to use anapole resonances in PICs, it would be desirable to see whether the anapole state can be excited by guided in-plane illumination (perpendicular to the disk axis), in a scheme similar to that previously used to excite resonances in plasmonic nanoantennas [7]. As shown in Fig. 1, we fabricated a circuit in which a silicon disk is excited from the side using an adjacent silicon waveguide. We have been able to measure the top scattering for different disk radii, which shows a strong reduction at wavelengths corresponding to the predicted anapole resonance, which depends on the disk radius. These results confirm the possibility to excite this radiationless mode in PICs.

III. Chiral Interfaces

Guided waves possess transversal spin [8,9], which can be used to select the direction of propagation by merely switching the spin of the excitation source in the near field. This phenomenon, known as spin-controlled unidirectional excitation (SCUE) of guided waves [10], is explained from spin-orbit interaction and can be used to create chiral interfaces in guided systems [11].

The system in Ref. [11] consists of a plasmonic nanoparticle (as a near-filed source) coupled to a tapered optical fiber and it is not suitable for on-chip integration. Since silicon waveguides also display transversal spin [12], SCUE and chiral interfaces are also expected to occur in PICs. In [13] we proposed and demonstrated experimentally a chiral interface on a silicon PIC. To achieve a large efficiency, we used a subwavelength silicon disk supporting a magnetic dipolar resonance that is easily coupled to the continuum of radiation modes (see Fig. 2). The disk was placed closely to a silicon waveguide so that the guided waves were directed towards one direction or the opposite path merely dependent on the spin (or handedness of circular polarization) of the light illuminating the structure from the top. The gap in the waveguide was created to maximize the conversion efficiency between free-space and guided waves. This concept can easily be extended to linearly polarized waves [14] and be even used to synthesize arbitrary polarization states of radiated light [15].

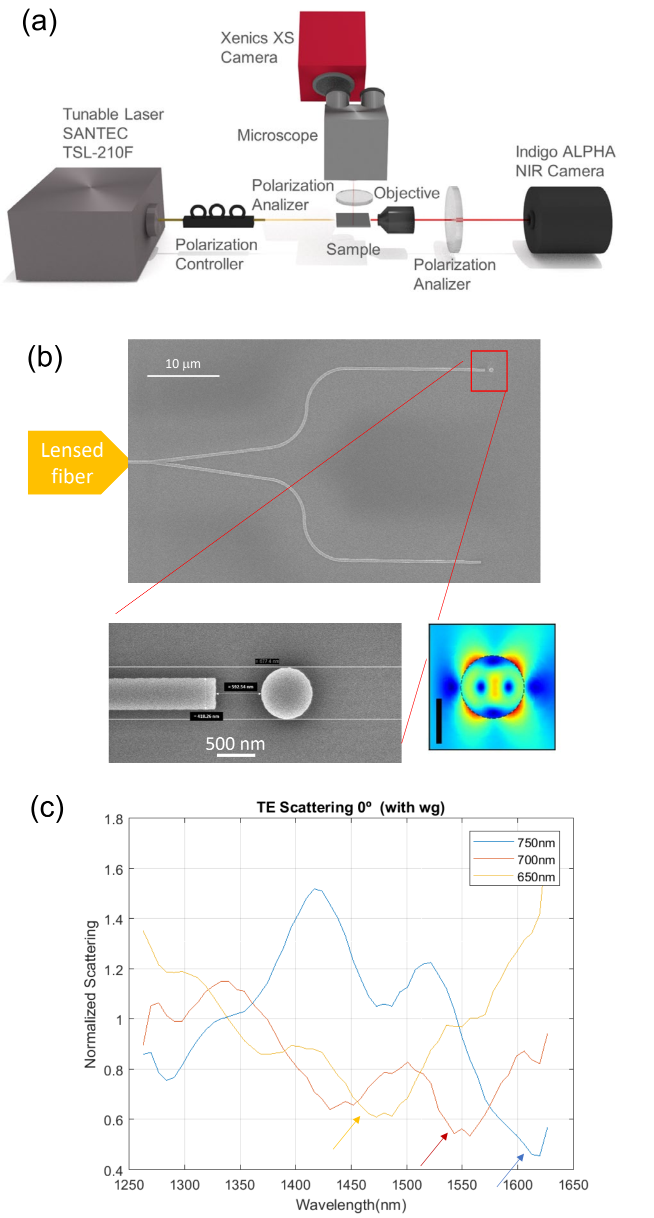

Fig. 1. On-chip anapole on a silicon disk. (a) Experimental set-up for far-field measurements in the direction of the disk axis; (b) SEM image of a fabricated circuit with and $r \approx 350$ nm, showing a path with disk and a path without disk. Inset: details of the disk and the exciting waveguide and calculated-near field map of the anapole; (c) Recorded normalized scattering for disks with $r = 325$, 350 and 375 nm. The anapole wavelengths (minimum of normalized scattering) are highlighted by the arrows.

IV. Enhanced Raman Scattering

As addressed above, interference between multipolar terms may lead to the cancellation of the scattering but also to the enhancement of near-fields, which should be useful in non-linear applications. In other applications such as sensing or Raman spectroscopy, strong near-fields are also pursued but not inside the particle but around its surroundings. This can be achieved when placing two disks very close to each other forming silicon dimers [16,17].

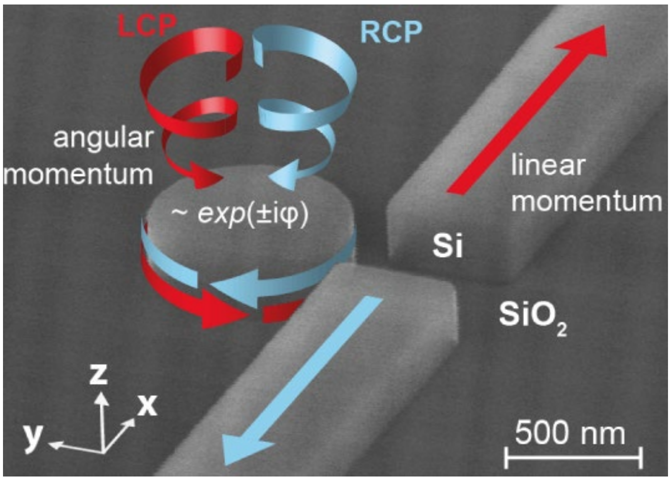

Fig. 2. Chiral interface using a silicon disk coupled to a waveguide. When illuminated from the top using either left-handed or right-handed circularly polarized (LCP, RCP) light, spin-orbit interaction converts angular momentum into linear momentum, and gives rise to SCUE of guided waves. The silicon disk supports a highly-radiative magnetic dipole resonance, which enables to increase the efficiency of the coupling.

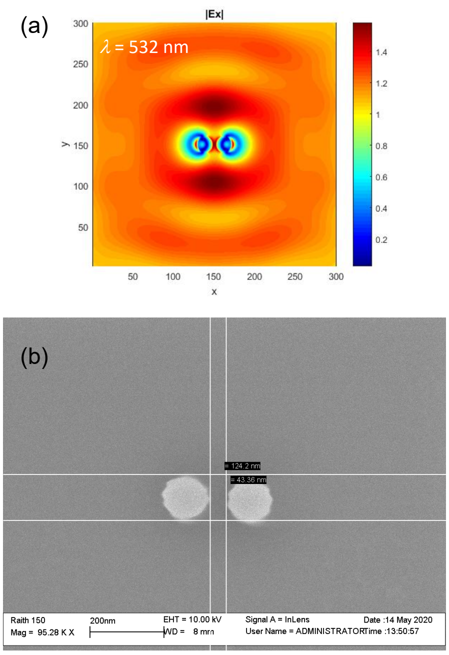

Fig. 3. Silicon disk dimers for enhanced Raman scattering. (a) Two silicon disks placed in close proximity can lead extremely localized electric fields in void regions, which could be highly useful in Raman spectroscopy and sensing; (b) SEM image of a fabricated silicon disk dimer aimed at producing enhanced Raman scattering at 532 nm.

As shown in Fig. 3(a), a silicon dimer with suitable dimensions can produce electric field hot-spots in the regions surrounding the disks. This means that the nonlinear response of any material placed in such hot-spots will be largely enhanced as a result of the extreme field concentration. Even though the hot-spots are not so strong as in the case of plasmonic nanoparticles, the use of dielectric materials displays some advantages, such as the reduced heating and degradation of the material and the ease for fabrication using conventional semiconductor lithographic techniques. Figure 3(b) shows the detail of a silicon dimer fabricated using electron beam lithography and dry etching. The gap between disks is about 40 nm, which is more than one order of magnitude smaller than the used wavelength (in this case, 532 nm). Using arrays of silicon disk dimers we have been able to measure Raman spectra of molecular monolayers, remarkably including 2D materials such as MoS_2.

V. Cavity Optomechanics

Cavity optomechanics addresses the interaction between optical and mechanical waves in deformable cavities [18]. The mechanical interaction typically induces a modulation of the optical field at the mechanical frequency, which can find use in microwave photonics. Typically, optomechanical cavities are fabricated in suspended high-index fields by introducing a periodicity that permits to confine optical and mechanical waves simultaneously [19]. This permits to obtain optical modes confined at telecom wavelengths and mechanical waves of several GHz, which interact with coupling rates g_0 of the order of 1 MHz or less [20]. This kind of structure has several constraints, including the difficulty of forming arrays and fabrication complexity. Also, reaching frequencies above 8 GHz (the relevant X band in wireless applications) is quite challenging.

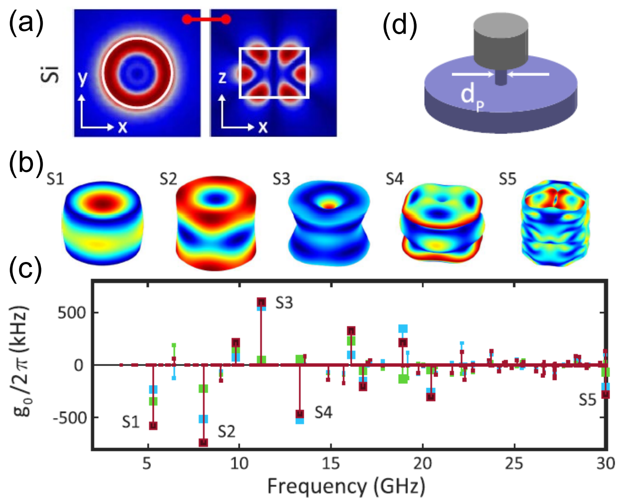

Fig. 4. Silicon disk optomechanics. (a) A thick silicon disk with t = 589 nm and r = 403 nm supports a supercavity mode at 1559 nm with a Q factor of 237; (b) Localized mechanical modes S1 to S5 with the corresponding frequencies and coupling rates in (c). (d) A thin silica pillar can support the disk on a PIC without degrading the optical and mechanical responses.

In [21], we suggest that silicon disks can overcome these limitations and become interesting elements for cavity optomechanics. On one side, the typically low Q factor in subwavelength disks can be enhanced by smartly choosing the dimensions to get destructive interference between Mie and Fabry-Perot modes and get a supercavity optical mode [22]. In our case, a silicon disk with t = 589 nm and r = 403 nm supports a supercavity mode at 1559 nm (Fig. 4(a)) with a Q-factor of 237. This disk has also a series of mechanical resonances whose displacement fields are shown in Fig. 4(b). The interaction between these mechanical modes and the optical field results in relatively large values of the coupling rate g_0 (Fig. 4(c)) reaching even mechanical frequencies close to 30 GHz. These simulation results are obtained for a silicon disk completely surrounded by air in order to confine the mechanical modes, which is not physically realizable. However, we also show that by sustaining the disk on a very thin silica nanopillar (Fig. 4(d)) the optical and mechanical modes remain quite the same whilst the structure becomes physically realizable.

VI. Conclusions

We have shown that silicon disks can host exotic phenomena at the nanoscale despite their simplicity. We are convinced that the ease of fabrication can lead to the use of these structures as basic building blocks in silicon PICS. Applications in sensing, Raman spectroscopy or microwave photonics can easily be envisaged.

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