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Laser Resonators, Microresonators, and Beam Control XXV

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Enhancing and tailoring light-matter interaction in the near-infrared by all-dielectric metasurfaces supporting silicon-slot quasi-bound state in the continuum modes

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ABSTRACT

Light-matter interaction is crucial in many application domains of nanophotonics, including biosensing, trapping at the nanoscale, nonlinear optics, and lasing. Many approaches, mainly based on photonic and plasmonic resonant structures, have been investigated to enhance and tailor the interaction, but those based on all-dielectric metasurfaces have several unique advantages: low loss, easy excitation and readout, possibility of engineering the optical field distribution with many degrees of freedom, and electric tuning. Here we show that properly designed all-dielectric metasurfaces can support silicon-slot quasi-bound states in the continuum modes resonating in the near-infrared, strongly confining light in air and, consequently, enhancing light-matter interaction. Some samples of the designed metasurface have been fabricated in a silicon-on-sapphire wafer by e-beam lithography and reactive ion etching. The optical characterization of the chip has confirmed the excitation of the quasi-bound state in the continuum resonant modes, with measured Q-factor values exceeding 700.

Keywords: Metamaterials, biosensing, bound states in the continuum, nanofabrication, silicon metasurfaces, symmetry-protected modes

1. INTRODUCTION

Light-matter interaction plays a pivotal role in science and technology, being crucial in lasers, sensing, spectroscopy, quantum information processing, and lasers. The most efficient approach for enhancing light-matter integration is that based on resonant structures, which can be implemented by using a wide range of approaches that have been extensively studied in the last decades[1,2]. Metasurfaces (MSs), which consist of an ensemble of subwavelength optical elements, termed as meta-atoms, with properly designed spectral and polarization responses, have the potential of extensively controlling light-matter interaction and are attracting an increasing research interest[3].

MSs can be properly designed to support bound states in the continuum (BIC) modes[4], whose unique features in the context of sensing have been recently proved[5]. Different classes of BIC modes can be excited in MSs, including the symmetry-protected BIC (SP-BIC) ones, which allow for high Q-factor values[6,7,8].

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The paper reports on an all-dielectric silicon-on-sapphire MS operating in the near-infrared (NIR), properly intended for enhancing light-matter interaction. The metasurface, which is formed by a periodic array of circular slot segments etched in a thin silicon layer on a sapphire (see Figure 1), supports a SP-BIC with very high field confinement in the circular slots. An eigenfrequency study, symmetry-analysis considerations, and full-wave light propagation simulations demonstrate the SP nature of the BIC silicon-slot mode[9]. Both simulations and experiments show that the resonance Q-factor can be modified by adjusting the degree of asymmetry in the metasurface unit cell. This is obtained by shortening the arc length of one of the two circular slots. Due to the nearly entire confinement of the electric field within the slots, the NIR resonant wavelength of the quasi-BIC (qBIC) mode exhibits a considerable dependency on the refractive index of the surrounding material, with a sensitivity of 435 nm/RIU for gas sensing[9]. The excitation of the silicon-slot qBIC mode is experimentally confirmed by examining the transmission spectra of a collection of samples manufactured with varying degrees of asymmetry. The measured spectra corroborate the correlation between the asymmetry and the qBIC mode resonant wavelength change.

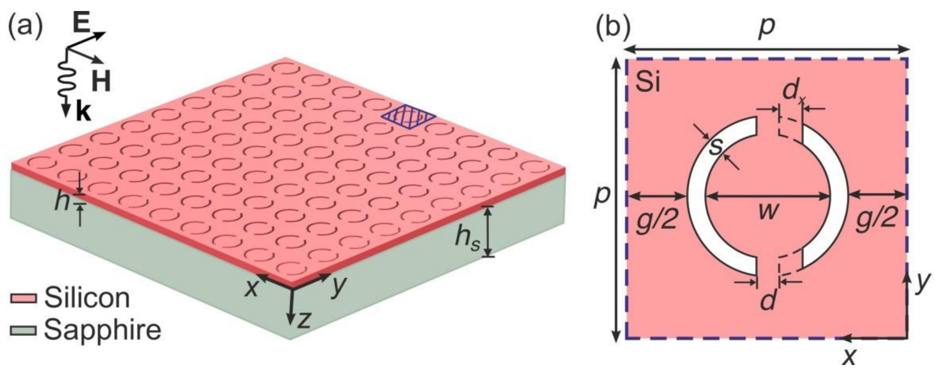

Figure 1. (a) Configuration of the all-dielectric silicon-on-sapphire metasurface. The incident planewave is y-polarized and impinges perpendicularly on the MS. (b) MS unit cell, which is formed by two segments of a circular slot ring with inner diameter *w* and slot width *s*. The distance between adjacent a circular slot rings is *g* and, the MS pitch is $p = w + g + 2s$. The CSR is interrupted by two symmetrical silicon bridges of width *d*. The length of one of the two slot segments is reduced by introducing the asymmetry parameter d_x, which asymmetrically increases the width of the silicon bridge. The thickness of the silicon layer is h = 200 nm. The thickness of the sapphire substrate is h_s = 430 µm.

2. SELECTED EXPERIMENTAL RESULTS

The design is based on full-wave and eigenvalue simulations using the finite-element method. The selected values for the geometrical parameters of the MS are s = 40 nm, g = 130 nm, w = 650 nm, and d = 80 nm. The simulations show that, for the BIC mode, the field is mostly concentrated inside the circular slot ring segments, resembling slot modes in slotted silicon nanowire waveguides.

The MS fabrication has been conducted in the nanofabrication facilities available at SiPhotonIC ApS following a standard e-beam lithography protocol. The samples have been manufactured on a silicon-on-sapphire wafer with a 200-nm thick silicon layer epitaxially grown on a 430-µm sapphire substrate.

The samples' transmittance has been measured under normal incidence of a polarized light beam using a Fourier-transform spectrometer with a spectral resolution of 0.25 pm.

The measured transmittance spectra for samples with varying degrees of asymmetry are shown in Figure 2. The ripple that can be observed in all spectra is due to Fabry-Perot oscillations in the sapphire substrate. The qBIC resonance is clearly visible for d_x down to 40 nm, whereas for lower values it is masked by the Fabry-Perot oscillation as well as by resonance damping. The measured Q-factors range from Q = 510 for d_x = 120 mn to Q = 725 for d_x = 40 nm. For $d_x \leq 20$ nm, smaller than the e-beam spot size, the qBIC is not detectable in the transmittance spectra due to complete quenching. The measured Q values are of the same order of magnitude compared to most experimental demonstrations of silicon-based qBIC meta-surfaces. They are significantly lower than the theoretical ones due to resonance damping, mainly due to statistical variations of the geometrical features of the fabricated metasurfaces.

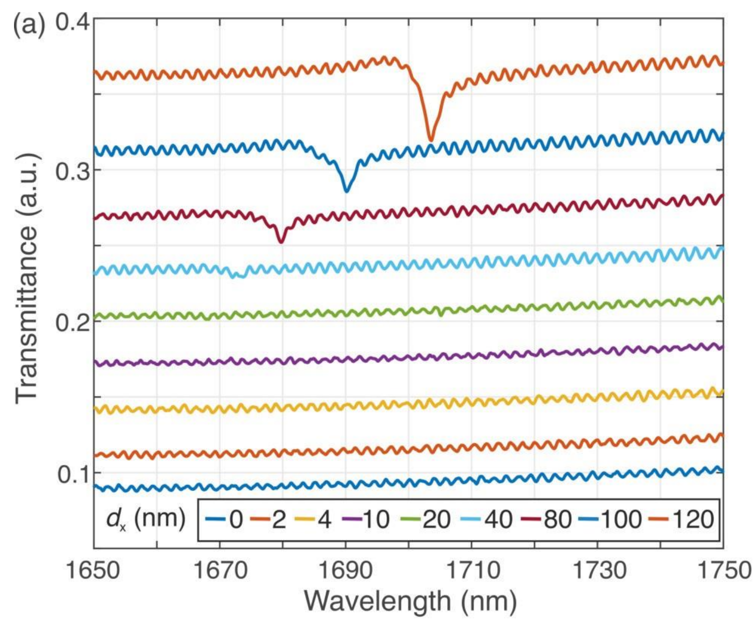

Figure 2. Transmission spectra for samples with different values of the asymmetry parameter d_x.

3. CONCLUSIONS

A silicon dielectric metasurface designed to enhance light-matter interaction and support a slot-like qBIC in the NIR with a Q-factor > 700 is reported. This experimental proof-of-concept demonstration introduces a new paradigm for the development of IR refractometric sensors and other devices based on enhanced light-matter interaction thanks to the strong optical field confinement in deeply subwavelength resonant cavities.

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