Experimental demonstration of a silicon-slot quasi-bound state in the continuum in near-infrared all-dielectric metasurfaces

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ABSTRACT
We theoretically and experimentally investigate a metasurface supporting a silicon-slot quasi-bound state in the continuum (qBIC) mode resonating in the near-infrared spectrum. The metasurface is composed of circular slots etched in a silicon layer on a sapphire substrate. The symmetry of the metasurface unit cell is reduced in order to provide access to the symmetry-protected mode, whose properties are investigated by finite-element full-wave and eigenfrequency analysis. The measured transmittance spectra verify the excitation of the investigated qBIC mode with experimental quality factors exceeding 700. The near-field distribution of the resonant qBIC mode shows strong field confinement in the slots, leading to high sensitivity values for refractometry.

1. Introduction

In recent years, bound states in the continuum (BIC) have developed into a new paradigm for trapping and confining resonant optical modes in photonic systems. In theory, pure BICs are dark states with infinite radiative lifetime in lossless systems with infinite structure [1] or permittivity approaching zero [2,3]. However, under realistic conditions, such as the finite extent of structures and material absorption, BIC manifest as Fano resonances with finite radiative and non-radiative quality factor (Q-factor) in what is termed as quasi-BIC (qBIC). Since their first theoretical [4] and experimental [5] demonstration in photonic systems, several works have investigated the underlying physics following theoretical frameworks [6].

Beyond the study of their fundamental physics, BIC have been increasingly applied in numerous breakthrough applications driven by advanced nanofabrication techniques [7]. The existence of optical BIC modes can be classified as symmetry-protected BIC (SP-BIC) [8], owing to symmetry-forbidden out-coupling, accidental or Friedrich-Wintgen BIC [9], as the outcome of radiation suppression of all open channels, and Fabry–Perot BIC (FP-BIC) [10]. Various photonic systems can support this diversity of BIC types [11]. Indeed, they have been thus far demonstrated in numerous geometrical configurations, including gratings [12], waveguides [13], photonic crystals [14] and metasurfaces [15].

Among these options, BIC-resonant metasurfaces are being extensively researched. Metasurfaces are two-dimensional arrangements of subwavelength optical scatterers capable of drastically modifying impinging wavefronts. In the case of dielectric metasurfaces, high-permittivity scatterers exhibit a variety of Mie resonances that allow for both electric and magnetic responses even at optical frequencies. For instance, the interaction among dipole resonances (namely, electric dipole, ED, magnetic dipole, MD, and toroidal dipole, TD) offers several possibilities, e.g., Huygens’ metasurfaces (interference of orthogonal ED and MD) [16], Janus dipole (interference of π/2 phase-shifted ED and MD) [17], and anapole states (interference of ED and TD) [18]. Being no exception, BIC modes too can be studied in terms of their multipole fingerprint, by employing appropriate tools such as the multipole...
decomposition technique, which has been used to investigate both SP-BIC and FW-BIC [6,19], as well as qBIC in dielectric nanostructures by coupling Mie resonances with FP cavity-like modes [20]. In a previous work, we proposed and investigated a SP-BIC resonating at telecom near-infrared (NIR) wavelengths in metasurfaces based on split ring ultrathin slots etched in silicon [21]. Although the metasurface investigated in this work belongs to the type introduced in [21], the presented study is fundamentally different as: (i) it regards the properties of a qBIC resonant mode of different symmetry, not studied in [21], (ii) it focuses on the refractometric performance of the proposed qBIC resonant metasurface, and, most important, (iii) it provides the first experimental results on split-ring silicon metasurfaces. In particular, we theoretically and experimentally demonstrate a SP-BIC with very strong field confinement in circular slots defined by electron-beam lithography (EBL) and fabricated via inductively coupled plasma (ICP) etching on a silicon-on-sapphire metasurface. First, the SP nature of the BIC silicon-slot mode is demonstrated through an eigenfrequency study, symmetry-analysis considerations and full-wave light propagation simulations. It is shown that the radiative Q-factor of the resonance can be adjusted by controlling the degree of asymmetry in the metasurface unit cell, which is introduced by reducing the arc length of one of the two constituent circular slots. Thanks to the almost total electric field confinement in the slots, the NIR resonant wavelength of the qBIC mode shows strong dependence on the refractive index of the surrounding material, with sensitivity equal to 435 nm/RIU in the case of gas sensing. The existence of the investigated silicon-slot qBIC mode is experimentally verified by measuring the transmission spectra of a set of fabricated samples with different degrees of asymmetry. The measured spectra confirm the trend in the variation of the qBIC mode resonant wavelength as a function of the asymmetry. Q-factors as high as 725 are measured and the possible factors leading to the observed resonance broadening are thoroughly discussed. This experimental proof-of-concept demonstration of a qBIC in silicon-on-sapphire metasurfaces introduces a new paradigm for the development of IR refractometric sensors or other devices based on enhanced light–matter interaction thanks to strong optical field confinement in deeply-subwavelength resonant cavities.

2. Design and theoretical analysis

The layout of the investigated MS is presented in Fig. 1(a). A periodic array of circular slot segments is etched in a thin silicon layer on a sapphire substrate. The incident plane wave is $\gamma$-polarized and it impinges perpendicularly on the MS. The MS unit cell, shown in Fig. 1(b), is composed of two segments of a circular slot ring (CSR) with inner diameter $w$ and slot width $s$. The distance between adjacent CSR is $g$ and, therefore, the MS pitch equals $p = w + g + 2s$. The CSR is interrupted by two symmetrical silicon bridges of width $d$, which reduces the 2D symmetry of the unit cell from $C_{4v}$ to $C_{2v}$ (in Schoenflies notation [22]). Then, the length of one of the two slot segments is reduced by introducing the asymmetry parameter $d_1$, which asymmetically increases the width of the silicon bridge, and lowers the symmetry of the structure to $C_2$. This symmetry reduction is necessary for the excitation of the investigated symmetry-protected qBIC resonant mode, as it will be further discussed. It is remarked that, although the introduction of the silicon gap $d$ is not sufficient to allow excitation of the target BIC mode, it facilitates the fabrication of the asymmetric samples ($d_1 \neq 0$), which is done by increasing the width of the existing silicon bridge. On the contrary, a single bridge of width $d_1$ in the range of few nanometers would pose serious fabrication challenges due to EBL resolution limitations.

Fig. 1(c) and (d) show the scanning electron microscope (SEM) images for two of the samples characterized by $d_1 = 0$ and $d_1 = 80$ nm, respectively. All samples were fabricated following a standard EBL nanofabrication protocol (details in Section 3). The design values for the geometrical parameters of the MS are: $s = 40$ nm, $g = 130$ nm, $w = 650$ nm, $d = 80$ nm, and $h = 200$ nm. Silicon and sapphire were modeled in the simulations through their refractive index $n_{Si} = 3.47$ and $n_i = 1.74$, respectively. In the theoretical analysis the sapphire substrate was treated as a semi-infinite medium.

The theoretical analysis consisted in full-wave and eigenvalue simulations using the finite-element method implemented in the commercial software Comsol Multiphysics. In all cases, only the MS unit cell was simulated by applying Floquet periodic boundary conditions at the lateral walls of the computational domain. As the focus was on normal wave incidence, the transverse components of the wavevector were set to zero ($k_x = k_y = 0$).

Fig. 2(a) shows the calculated full-wave transmittance spectra in the vicinity of the target qBIC resonance for various values of $d_1$, evidencing the reduction of the resonance linewidth for decreasing values of $d_1$. The transmittance spectra were fitted to the following Fano formula

$$T_{\text{Fano}}(\omega) = \frac{|d|^2}{(\omega_{\text{res}} - \omega + \gamma_0)^2 + \omega_{\text{res}}^2 + \gamma_0^2},$$

where $\omega_{\text{res}} = \omega/\omega_{\text{res}}$ is the normalized angular frequency, $\omega_{\text{res}} = 2\pi c/\lambda_{\text{res}}$, $\gamma_0$ being the resonant wavelength, $c_0$ the speed of light in free space, $F$ the Fano asymmetry parameter and $\gamma_0$ the damping rate through which the Q-factor can be directly calculated as $Q = 1/2\gamma_0$. In all cases, excellent fitting was achieved, as demonstrated in the indicative case of $d_1 = 100$ nm shown in the inset of Fig. 2(a).

Moreover, an eigenfrequency analysis was performed, aiming to complement the full-wave/Fano-fitting results. The analysis provided the resonant wavelength and Q-factor of the qBIC resonance as a function of $d_1$ by calculating the corresponding complex qBIC eigenfrequency $\tilde{\omega} (Q = R(\tilde{\omega})/2|\tilde{\omega}|)$. Fig. 2(b) and (c) shows the dependence on $d_1$ of the resonant wavelength and radiative Q-factor, respectively, demonstrating very good agreement. As expected for symmetry-protected qBIC resonances, the Q-factor increases dramatically for small degrees of asymmetry and asymptotically tends to infinity due to vanishing radiation losses, under the assumption of lossless materials. In the small perturbation regime, the Q-factor follows the inverse quadratic law with respect to the asymmetry parameter $d_1$, shown as the dashed line in Fig. 2(c), which is a characteristic property of symmetry-protected, non-diffracting qBIC metasurfaces [23]. For larger values of $d_1$, the Q-factor drops faster as the asymmetric unit cell cannot longer be considered as a weak perturbation [24]. The resonant wavelength increases for higher values of $d_1$, as part of the air slot is substituted by high-index silicon in the volume of the unit cell.

The eigenfrequency analysis also provides an efficient tool to inspect the electric field profile of the BIC mode, which is shown in Fig. 3(a) for the symmetric structure ($d_1 = 0$), calculated at the midplane of the silicon layer ($z = h/2$) and at the $x = p/4$ cross-section plane. The field is mostly concentrated inside the CSR segments, resembling slot modes in slotted silicon nanowire waveguides. The arrows show the direction of the electric field (in logarithmic scale) and they reveal the electric quadrupole nature of the resonant BIC mode. Close inspection of the field profile around the field minima positions reveals only slight differences among the two regions occupied by the silicon bridge and those in the slots. The modal eigenfield profile shows the same symmetry as the structure ($C_{2v}$), although the perturbation with respect to $C_{4v}$ is small, since the silicon bridges occupy regions with low field intensity. This particular aspect of the slotted mode field profile implies that the introduction of the asymmetry parameter $d_1$ is expected to only slightly perturb the resonant field, thus allowing for larger values of $d_1$ to achieve a given degree of coupling to the resonant mode.

The symmetry properties of such SP-BIC modes can be analyzed by means of the symmetry adapted linear combination (SALC) method [25, 26]. The irreducible representation (IRREP) of this mode is $B_2$ in the group $C_{4v}$ and reduces to $A_1$ in $C_{2v}$. However, in both cases the incident field $E$ belongs to a different IRREP ($E$ and $B_1$ for $C_{4v}$ and
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Fig. 1. (a) Bird’s eye view of the investigated silicon-on-sapphire metasurface. The metasurface is composed of split-ring slot segments etched in a $h = 200$ nm silicon layer grown on a $h_s = 430$ μm sapphire substrate. (b) Geometry of the metasurface unit cell. The symmetry is broken by shortening the arc length of one of the two slots via the asymmetry parameter $d_x$. (c) Scanning electron microscope images of two fabricated samples corresponding to the symmetric metasurface ($d_x = 0$) and one with broken symmetry ($d_x = 80$ nm).

Fig. 2. (a) Full-wave calculated transmittance spectra of the metasurface around the qBIC resonance for various values of $d_x$. The spectra were fitted to the Fano formula of Eq. (1) with excellent fitting, as evidenced in the inset for $d_x = 100$ nm. (b) Variation of the resonant wavelength and (c) $Q$-factor of the qBIC mode calculated by eigenfrequency analysis and by the corresponding Fano parameters of the fitted full-wave spectra.

Fig. 3. (a) Electric field profile of the BIC eigenmode calculated at the silicon layer midplane of the metasurface and the $x = \pi/4$ plane, demonstrating the silicon-slot nature of the mode. The arrows (in log scale) show the direction of the electric field and reveal an electric-quadrupole type mode. (b) Variation of the resonant wavelength calculated by eigenfrequency analysis as a function of the superstratum refractive index. The sensitivity value is $S = 435$ nm/RIU and it is linear in the investigated interval.

$C_{2v}$, respectively) and hence the mode cannot be excited. Reduction to $C_1$ symmetry by introducing $d_x \neq 0$ degenerates the BIC mode IRREP to $B$, which coincides with that of the field $E_y$, thus enabling polarization-selective excitation as a qBIC resonance.

The silicon-slot character of the qBIC mode leads to strong interaction of the resonant field with the material occupying the slots. This property can be directly exploited in refractometric sensing by filling the slots with the analyte material. To provide an estimate of the sensitivity of such a sensing platform, defined as $S = \Delta \lambda_{res}/\Delta n_a$, where $n_a$ is the analyte refractive index, we have calculated $\lambda_{res}(n_a)$ employing eigenfrequency analysis for the symmetric MS. The variation of $n_a$ was from 1 to 1.1, which corresponds to the scenario of gas sensing. Fig. 3(b) demonstrates a high value of sensitivity $S = 435$ nm/RIU with an almost perfectly linear profile, a highly desirable trait in sensing applications. The high sensitivity can be, in principle, combined with very high $Q$-factor values, thus leading to a figure of merit (FoM = $Q S/\lambda_{res}$) orders of magnitude higher than, for instance, sensors based on plasmonic architectures, which suffer from ohmic damping losses [27]. In the context of gas refractometry, it is remarked that the variation of the refractive index $n_g$ of standard gases ($N_2$, $O_2$, $H_2$, $CO_2$, $CH_4$, $He$) lies in the interval $1 < n_g < 1.001$ [28]. Given the abovementioned sensitivity values, the proposed gas sensor would need a spectral resolution in the order of few tens of picometers to discern among various gases. In a real system, the sensor resolution is limited by amplitude noise, thermal fluctuations and the spectral limitation of the detector [29]. Regarding the later, high-resolution optical spectrum analyzers (OSA) offer sub-pm resolution and, hence, standard deviation values [30]. Temperature stabilization can result also in sub-pm standard deviation. The standard deviation of the spectral variation due to amplitude noise can be estimated as $\sigma \approx \Delta \lambda/(4.5 \text{SNR}^{0.25})$, where $\Delta \lambda$ and SNR are the resonance linewidth and signal-to-noise ratio (in linear units), respectively [29]. Considering the conservative value of SNR=60 dB and the $Q$-factors experimentally measured for the investigated qBIC metasurface (ranging from 500 to 725, details in Section 3), the resonance linewidth is $\Delta \lambda \approx 3$ nm and the calculated...
sensor resolution, established as 3σ of the noise in the system, is in the order of 60 pm, which is compatible with operation as a gas sensor. Significant margins of improvement exist in terms of increasing both the sensitivity and the Q-factor, as it will be thoroughly discussed.

Dielectric metasurface refractometric sensors offer direct integration with microfluidic setups, e.g., polydimethylsiloxane (PDMS) chambers, and free-space coupling for simple read-out, hence they have been intensively researched following various approaches, such as qBIC, bright, or guided-mode resonances. Table 1 summarizes the recent progress in the field by providing the key performance indicators of bulk refractometric sensors, namely S, Q-factor, and FoM. The calculated S for the investigated qBIC metasurface sensor, as well as its FoM, as estimated based on the highest measured value Q = 725, favorably compare to most of the reported cases, although a direct comparison is not fully consistent as the sensors reported in Table 1 target mostly biosensing applications with analyte refractive indices ~1.3. Furthermore, the geometry of the silicon-slot metasurface has not been optimized in terms of the maximum sensitivity. For instance, just by replacing sapphire with standard silica as the substrate, simulations showed that the sensitivity increases to 518 nm (λres = 1598.6 nm to 1650.4 nm for nSi = 1 to 1.1), thanks to the lower refractive index of silica.

3. Experimental results

The fabrication was carried out in the nanofabrication facilities at SiPhotonIC ApS. The investigated devices were fabricated on a silicon-on-sapphire platform with a 200 nm thick silicon layer epitaxially grown on a 430-μm-thick sapphire substrate. The nanoslots were defined by EBL using CSAR e-beam resist and the JBX-9500FSZ kV E-Beam Writer. After EBL, the STS ICP Advanced Silicon Etcher (ASE) was applied to an etching phase with CSAR e-beam resist and the JBX-9500FSZ kV E-Beam Writer. The light beam from the spectrometer was focused on the sample surface with an Al off-axis parabolic mirror to a spot-size diameter of 100 μm, with an angular spread of ±0.5 deg. A liquid-nitrogen-cooled InSb photodiode was used as the detector.

![Image](https://via.placeholder.com/595x793.png)

### Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Structure</th>
<th>S [nm/RIU]</th>
<th>Q</th>
<th>FoM Ref.</th>
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<td>SOI photonic crystal slab</td>
<td>94</td>
<td>12000</td>
<td>735</td>
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<tr>
<td>2018</td>
<td>Si,Ni photonic crystal slab</td>
<td>178</td>
<td>2000</td>
<td>445</td>
</tr>
<tr>
<td>2018</td>
<td>SOI nanodisks</td>
<td>720</td>
<td>270</td>
<td>120</td>
</tr>
<tr>
<td>2019</td>
<td>Si2N2O2 guided-mode metasurface</td>
<td>235.2</td>
<td>600</td>
<td>12.3</td>
</tr>
<tr>
<td>2020</td>
<td>Si hollow nanocuboids</td>
<td>161.5</td>
<td>728</td>
<td>78</td>
</tr>
<tr>
<td>2020</td>
<td>TiO2 nanobars</td>
<td>80.6</td>
<td>852</td>
<td>80.6</td>
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<td>2021</td>
<td>SOI tilted Si nanoellipsoids</td>
<td>788</td>
<td>100</td>
<td>90</td>
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<tr>
<td>2021</td>
<td>Si crescent-shaped nanocylinders</td>
<td>326</td>
<td>120</td>
<td>52</td>
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<td>2021</td>
<td>Si asymmetric nanoellipsoids</td>
<td>305</td>
<td>179</td>
<td>68</td>
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<tr>
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<td>nanoholes in a-SiO2 film</td>
<td>145</td>
<td>450</td>
<td>94</td>
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<td>2022</td>
<td>Si tilted nanobars</td>
<td>608</td>
<td>102</td>
<td>46</td>
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<td>2022</td>
<td>Si slotted rings</td>
<td>435</td>
<td>725</td>
<td>189</td>
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*Estimation based on the calculated sensitivity and maximum measured Q-factor.

The transmittance of the various samples was measured under normal incidence of a polarized light beam using a Fourier-transform spectrometer (Bruker IFS66) with a spectral resolution of 0.25 pm (1 cm⁻¹). The light beam from the spectrometer was focused on the sample surface with an Al off-axis parabolic mirror to a spot-size diameter of 100 μm, with an angular spread of ±0.5 deg. A liquid-nitrogen-cooled InSb photodiode was used as the detector.

![Image](https://via.placeholder.com/595x793.png)

Fig. 4. (a) High-resolution SEM image of the d₀ = 0 nm sample showing the details of two adjacent slots etched in the silicon layer. (b) SEM image of the vertical cross-section of the d₀ = 80 nm sample taken after FIB processing.

In order to estimate the qBIC resonance Q-factors, the measured transmittance spectra were fitted to

\[
T(\omega) = A(\omega) + F(\omega),
\]

where \(A(\omega)\) is the Airy function that describes the background Fabry–Perot interference in the sapphire substrate [42] and \(F(\omega)\) is the extended Fano formula [43]

\[
F(\omega) = \frac{\eta_{\text{rad}}}{\eta_{\text{abs}}} - \frac{\eta_{\text{rad}}\eta_{\text{abs}}}{1 + \left(\frac{\omega - \omega_0}{\gamma}\right)^2} + \eta_{\text{abs}}|\beta|^2.
\]

where \(\beta\) is the intensity of the resonant transmittance at \(\omega_0\) and \(\eta_{\text{rad}}, \eta_{\text{abs}}\) are the radiation and absorption probabilities, respectively, of the
due to complete quenching. The measured $Q$-beam spotsize, the qBIC was not detectable in the transmittance spectra $Q = 725$ will be discussed shortly after.

**Figure 5.** (a) Experimentally measured transmittance spectra for the fabricated metasurface samples. The qBIC resonant is evident for higher values of $d_x$. The ripples are due to the Fabry–Perot effect in the sapphire substrate. (b) The fit of the $d_x = 120$ nm and $d_x = 40$ nm spectra to the transmittance formula of Eq. (2).

**Table 2**

<table>
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<tr>
<th>Year</th>
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<td>1300</td>
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<td>[46]</td>
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<td>1345</td>
<td>[48]</td>
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<td>1450</td>
<td>[49]</td>
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<td>1278</td>
<td>[50]</td>
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<td>[51]</td>
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<td>[52]</td>
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<td>silicon slotted rings</td>
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*Limited by measurement resolution.

localized qBIC mode ($n_{rad} = 1 - n_{thb}$). Fig. 5(b) shows the comparison between the measured spectrum for $d_x = 120$ nm and the fitted Fano function, which is capable of resolving the linewidth of the qBIC resonance. It is stressed that Eq. (3) serves as a mathematical tool to quantify the measured $Q$-factors and does not provide the complete picture of the involved physics that lead to resonance broadening, as it will be discussed shortly after.

The fitted $Q$-factors range from $Q = 510$ for $d_x = 120$ nm to $Q = 725$ for $d_x = 40$ nm. For $d_x \leq 20$ nm, namely smaller than the e-beam spotsize, the qBIC was 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 metasurfaces (although not based on silicon-slot resonances), with the notable exceptions of the truncated nanocuboid metasurface paradigm [47,50,54] and the concept of merging BIC in photonic crystal slab structures [46,52]. Table 2 summarizes recent progress in the field and places the results of this study in the context.

The measured $Q$ values are significantly lower than the theoretical ones due to resonance damping. The latter may stem from various factors [56], of which one of the most critical is often statistical variations of the geometrical features of the fabricated metasurfaces [57]. We have conducted an investigation by post-processing SEM images such as in Fig. 1(b) and Fig. 4 (more examples shown in Section 1 of the Supplementary Information) on the slot width $s$, as this was found to be the most sensitive parameter in terms of defining the qBIC resonance wavelength $\lambda_{res}$. A quasi-normal statistical distribution was observed with a standard deviation of $\sigma_s = 2.41$ nm (see Section 2 of the Supplementary Information). Fig. 6(a) shows simulation results on the dependence of $\lambda_{res}$ as a function of $d_x$ and the slot width, where $\Delta s$ is the variation from the nominal value of $s_0 = 40$ nm, namely $s = s_0 + \Delta s$. It is demonstrated that for the indicative case $\Delta s = \pm 5\%$, the qBIC resonant wavelength varies in the order of $\Delta \lambda_{res}/\lambda_{res} \approx 1.5\%$, almost independently of $d_x$. Although an accurate estimate of the induced resonance broadening, as for instance described in Ref. [57], is beyond the scope of this work, the level of variation in $\lambda_{res}$ considering the measured statistical distribution accounts for the measured $Q$-values, which are limited below 1000.

Other factors that may contribute to the observed resonance damping are: (i) scattering losses caused by etching-induced surface roughness of silicon at the slot walls, (ii) the finite lateral extent of the metasurface, and (iii) the small angular spread of $\theta_s = 0.5^\circ$ of the probing beam.
light beam. The latter two factors cause resonance broadening owing to the fact that they lead to the excitation of the qBIC resonant mode at off-$\Gamma$ k-vector points, which have different resonant wavelengths due to the dispersion of the qBIC mode. This spectral broadening (as previously observed [42]) limits the maximum observable $Q$-factor according to the following constrain:

$$Q \leq \frac{\omega_{res}}{\Delta k \cdot \Delta \omega} \cdot b^2$$  \hspace{1cm} (4)

where $\Delta k$ is the wavevector spread and $b = \frac{1}{2} \frac{2\pi m}{\Delta k \cdot \Delta \omega} [26]$. In the case of a non-collimated probe beam with an angular spread $\theta_h$, the wavevector spread equals $\Delta k_h = k_{res} \sin \theta_h$, where $k_{res} = 2\pi/\lambda_{res}$. In the case of a finite-size metasurface, the $k$-spread stems from the perturbation of the resonant mode in the finite structure, which leads to a wavevector fluctuation $\Delta k_b \approx 2\pi/L$ off the $\Gamma$ point in the quantized $k$-space, where $L$ is the lateral size of the metasurface [58,59]. Since the fabricated samples have $L = 0.3 \text{ mm}$, $\lambda_{res} \approx 1.665 \text{ nm}$, and $\theta_b = 0.5^\circ$, it follows that $\Delta k_b \approx \Delta k_b$, hence the $Q$-factor is in this case limited by the beam angular spread.

To estimate the maximum measurable $Q$-factor, the dispersion $\omega_{res}(k)$ of the investigated qBIC around the $\Gamma$-point is calculated for the symmetric structure and for variations of both $k_x$ and $k_y$. The results, shown in Fig. 6(b), demonstrating a parabolic-type dispersion, is larger for variations of the $k_y$ wavevector component. The corresponding parameter $b$ is estimated at $b_y \approx 40 \text{ m}^2/\text{s}$ and the maximum $Q$-factor is $Q_{max} \approx 26000$, which is more than one order of magnitude higher than the measured values. Hence, we attribute the observed resonance damping primarily to fabrication limitations, both in terms of geometrical feature definition/etching profile and their statistical variation over the metasurface area, most notably that of the slot width. Nevertheless, the results clearly demonstrate the scope of this work, which was the experimental verification of the investigated silicon-slot qBIC resonant mode in the proposed dielectric metasurfaces.

4. Conclusions

To sum up, this work provides a theoretical and experimental investigation of a silicon dielectric metasurface designed to support a slot-like qBIC in the near IR. Thanks to the qBIC nature and intense field confinement in the metasurface slots, the resonant mode provides both high sensitivity and $Q$-factors by controlling the degree of asymmetry in the design of the unit cell. The main properties of the proposed qBIC mode were experimentally verified by measuring the transmittance of samples with varying degree of asymmetry, fabricated by EBL on a silicon-on-sapphire substrate. The measured $Q$-factors showed notable resonance damping stemming from various factors that are discussed in detail. The proof-of-concept demonstration of this silicon-slot qBIC resonant mode in dielectric metasurfaces can stimulate the engineering of metasurface-based devices for refractometry or other applications demanding strong field confinement in nanometric resonant volumes.

CRediT authorship contribution statement

J.F. Algorri: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. F. Dell’Olio: Conceptualization, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. Y. Ding: Investigation, Resources, Writing – review & editing, F. Labbé: Investigation, Writing – review & editing. V. Dmitriev: Formal analysis, Writing – review & editing, Supervision, Funding acquisition. J.M. Sánchez-Pena: Writing – review & editing, Funding acquisition. L.C. Andreani: Software, Formal analysis, Resources, Data curation, Writing – review & editing, Visualization, Supervision. M. Galli: Investigation, Resources, Writing – review & editing. D.C. Zografopoulos: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References


