Hybrid Photonic–Plasmonic Bound States in Continuum for Enhanced Light Manipulation

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Light can be influenced by permittivity changes in optical resonators to enable optical sensors, modulators, and switches. The best performance (intensity change per permittivity change) is observed for dielectric bound states in the continuum (BICs). However, the lateral size must be large to explore their full potential. In this work, hybrid photonic–plasmonic BICs (hybrid BICs) fabricated using a cost-efficient scalable fabrication method are experimentally realized. While plasmonics is known to enable strong miniaturization, regarding BICs, the introduction of losses is thought to reduce device performance. Hybrid BICs in two operation modes, specular geometry and diffraction geometry, are also theoretically analyzed. While the reduced device performance is confirmed for hybrid BICs investigated in a specular geometry, a different result is obtained using diffraction geometry: hybrid BICs using diffraction geometry exhibit greatly increased performance compared to purely dielectric ones. Hybrid BICs using diffraction geometry as powerful tool to enhance the capability of light manipulation are thus considered.

Optical resonators have been established as the most advanced platform for optical sensors and modulators, and they come in a broad variety of different resonator types, including localized[1–3] and delocalized plasmons,[4] photonic crystal cavities,[5,6] guided mode resonances,[7] ring resonators,[8] and dielectric whispering gallery mode resonators.[9–11]

Their performance is commonly evaluated by a figure of merit (FOM*) that is given by the relative change of a measured intensity or power signal[12]

\[
FOM^* = \frac{1}{Q} \frac{\partial P}{\partial n} \propto QS
\]  

(1)

To achieve high performance, high quality factors \( Q = \frac{\lambda}{\Delta \lambda} \) and a large shift of the central resonance wavelength with respect to permittivity changes—labeled as sensitivity \( S = \partial \lambda / \partial n \)—are desired simultaneously.

However, dielectric systems tend to have high values of \( Q \) and low values of \( S \) while plasmonic systems behave oppositely, thus limiting the achievable FOM*. Notably, hybridizing dielectric and plasmonic resonators has often been considered to circumvent this limit.[9,13–23] The resulting hybrid resonators exhibit mediocre values of \( Q \) and \( S \) and, although hybrid resonators still resemble a large ongoing field of research due to their benefits of cost efficiency, none of these hybrid resonators have shown superior performance in comparison to the individual uncoupled resonators to date.

Remarkably, dielectric bound states in continuum (BICs) exhibit a higher FOM* than could be achieved by coupling of two optical resonators with initial quality factors and sensitivities \( Q_1, S_1 \) and \( Q_2, S_2 \) (see Supporting Information).[24–26] This is a consequence of the destructive interference of at least two waves with a common output channel mathematically described by a coupled mode Hamiltonian (see Supporting Information).[24,27] The radiative component of \( Q \) diverges at an exceptional frequency while \( S \) remains unaffected, thus leading to a strongly increased FOM*. As a result, BICs provide high performance, which has been utilized for lasers,[24,28,29] sensors,[10,31] and filters.[32]

However, the BIC is a mathematical singularity, which only reaches infinite \( Q \)-factors for infinitely large perfect dielectric photonic crystals under perfectly parallel irradiation (infinite radiance). To date, the fabrication of high-quality dielectric photonic crystals requires the utilization of top-down methods such as e-beam lithography or reactive ion beam etching, which are only applicable for small areas.[25,29,10,13–36] Reducing the necessary device size for BICs and finding upscaleable fabrication methods are thus key challenges in BIC research.

Plasmonics is widely known as being capable of reducing the dimensions of optical systems, thus appearing attractive for achieving BICs with shorter propagation lengths than dielectric systems. Recently, Azzam et al. have theoretically predicted the existence of hybrid photonic–plasmonic bound states in continuum (hybrid BICs) in hybrid waveguides.[37] However, the hybrid BICs would show strongly reduced FOM* for conventional device geometries utilizing their specular reflection and transmission properties (see Supporting Information).

In the present paper, we report two advances on hybrid BICs. First, we provide a strategy for fabricating the otherwise technically challenging hybrid waveguides via cost-efficient methods on large scales and provide the first experimental evidence for the existence of the proposed hybrid BICs. Second,
we theoretically show, as an example for enhanced light manipulation, that—for every device size—the performance FOM* of integrated hybrid BIC sensors will be approximately one order of magnitude higher compared to dielectric BICs.

Before its fabrication, we planned the design of the proposed hybrid waveguide using a rigorous coupled-wave analysis simulation.[38] The proposed hybrid waveguide consists of a dielectric core of thickness \( t_{\text{core}} = 2130 \text{ nm} \) with a thin silver film of thickness \( t_{\text{ag}} = 60 \text{ nm} \) in its exact center and a lower index dielectric cladding surrounding the core. This design is visualized in Figure 1a. Its symmetry ensures the topological protection of hybrid BICs. The following simulated values were obtained by using OrmoCore as core material and Borofloat glass as cladding material. Their optical constants used for glass and OrmoCore were calculated according to the Cauchy-model

\[
n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda} + i n_i(\lambda)
\]  

(2)

with \( A_{\text{glass}} = 1.4613 \), \( B_{\text{glass}} = 0.00299 \ \mu\text{m}^2 \), and \( A_{\text{OC}} = 1.533 \), \( B_{\text{OC}} = 0.00617 \ \mu\text{m}^2 \), and \( C = 0 \) for both materials. Material losses described by \( n_i(\lambda) \) were implemented according to the data sheet of the manufacturer (SCHOTT) for glass and self measured data for OrmoCore (see Supporting Information). In the spectral range of interest, their values are approximately \( n_i \approx 6 \) for silver, \( n_i = 7.3 \times 10^{-7} \) for OrmoCore, and \( n_i = 3.2 \times 10^{-7} \) for glass. For modeling silver, the optical constants published by Palik were used.[39]

At the energy range of interest, the hybrid waveguide supports two propagating photonic modes and two plasmonic modes, respectively, as indicated by the dispersion relation presented in Figure 1b. Since the hybrid waveguide is mirror symmetric, the magnetic field distributions shown in Figure 1c are either symmetric or antisymmetric with respect to the \( z = 0 \) plane. The symmetric and antisymmetric photonic modes, with respective Q-factors of 5560 and 2120 and rather low values of \( S \) of 41 and 76 nm per refractive index unit (RIU), are labeled as \( \text{PH}_s \) and \( \text{PH}_a \), while the plasmonic modes possess low Q-factors of 535 and 160 combined with large sensitivities of 503 and 700 nm per RIU and are termed symmetric surface plasmon polariton (SPPs) and antisymmetric surface plasmon polariton (SPPa).[40]
To achieve hybrid BICs, the SPP and PH modes must be coupled with a complex-valued coupling constant. This is accomplished by a sinusoidal modulation of the silver film (Figure 1d), which leads to the formation of an optical band structure.\(^{[41]}\) Additionally, such a modulation provides time-reversal symmetry as well as mirror symmetry under glide operations, which is described by the following expression

\[
\varepsilon(x + \delta y, -z) = \varepsilon^*(x, y, z)
\]

Together with the symmetric dielectric environment around the silver film, this ensures topologically protected BICs due to equal Fourier amplitudes in both the \(z\) and \(-z\) direction.\(^{[25,42]}\) Consequently, changes in permittivity or geometry lead to a shift of the BIC position in the energy-momentum space only, without affecting its stability. Here, this modulation is characterized by an amplitude \(t_{\text{grating}} = 100\) nm and a periodicity of \(\Lambda = 555\) nm.

The simulated coupling between the modes manifests as an anticrossing of their dispersion curves in the resulting band structure of the hybrid waveguide (Figure 1e). Spectrally distant from the position of anti-crossing, the diffraction into free space radiation becomes visible as strong periodic distortions of the cross-sectional field amplitudes, as shown in Figure 1f. These distortions can be understood as sources for the formation of plane waves emitting power into the radiation continuum. They build a common output channel for both the SPP and PH modes. For the majority of the calculated frequencies and momenta, the emission of power into this output channel causes substantially lower \(Q\)-factors than for the undisturbed modes of the planar geometry in Figure 1c.

However, toward a distinct frequency and momentum near the position of anticrossing, the \(Q\)-factor along the PH\(_4\)-dispersion curve (Figure 1g) exhibits a strongly pronounced maximum of a value of 2520. We observe that this maximum occurs as the result of the divergence of the radiative component of the \(Q\)-factor, labeled \(Q_r\). In accordance with this divergent \(Q_r\), the corresponding cross-sectional field amplitude at this distinct frequency in Figure 1h shows an undisturbed evanescent field decay in the waveguide claddings, thereby proving that losses due to radiation into free space modes are completely suppressed by destructive interference between the SPP\(_s\) and PH\(_s\) modes. This confirms that a hybrid BIC is indeed formed by the coupling of a photonic high \(Q\) mode and a plasmonic high \(S\) mode in the proposed hybrid waveguide.

The realization of such symmetric hybrid waveguides is technologically challenging. It requires the fabrication of metallic volume structures that are perfectly centered in a photonic waveguide. We identified polymer technology and mechanical structuring methods (see Figure 2a) to be perfectly suited for this purpose.

For the dielectric cladding and dielectric core, we chose glass and OrmoCore (OC), respectively. OrmoCore is cross-linkable by ultra-violett (UV) irradiation, and its Young’s modulus can be controlled by the applied UV dose. We use this property to fabricate a hardened waveguide with a nanoimprinted and subsequently metalized volume grating as well as a waveguide with a mechanically soft and equally thick OrmoCore layer. When
both waveguides are mechanically pressed together, the soft OrmoCore layer adapts to the curvature of the volume grating and then hardens under a final UV irradiation step, resulting in a symmetric hybrid waveguide. All these steps are upscalable, provide perfect centering of the silver film, and are even suited to achieving freestanding waveguides, where the low index glass substrates are removed resulting in a waveguide air/OC/Ag/OC/air. Such a freestanding waveguide laminated to silicon is presented in Figure 2b. Further details on the fabrication procedure are provided in the Experimental Section.

Following this procedure, we successfully fabricated a symmetric hybrid glass/OC/Ag/OC/glass waveguide. The structured area of the hybrid waveguide was nearly identical to the size of the imprint stamp (2.5 $\times$ 2.5 cm²), thus demonstrating the large area compatibility of the fabrication method (see Supporting Information). An scanning electron micrograph (SEM) of the cross-section (see Figure 2b) confirms the symmetry of the waveguide as well as the sinusoidal shape of the silver film.

The glass/OC/Ag/OC/glass hybrid waveguides were investigated by angle-resolved reflection and transmission spectroscopy to obtain their optical properties. The resulting spectra of the optical reflection $R$ and absorption $A$ of the hybrid waveguide (Figure 2c,d) exhibit spectrally distinct Fano-shaped resonances, respectively Lorentz resonances, which vary with different incident angles. At normal incidence, the resonances around a wavelength of 843 nm correspond to a real part of the effective refractive index $Re(\eta_{eff}) = 1.518$, indicating photonic modes guided by total internal reflection.[43] The other resonance around 885 nm leads to $Re(\eta_{eff}) = 1.594$ and coincides with the theoretical value of $Re(\eta_{eff}) = 1.594$ of surface plasmon polaritons propagating along the interface between silver and OrmoCore.[44] Away from normal incidence near $\theta = 3.9^\circ$ and $\lambda = 867$ nm, a transition of photonic modes into surface plasmon polaritons with increasing incident angle is observed, which indeed indicates coupling between photonic and plasmonic modes, as predicted in Figure 1. A comparison with the spectra of a simulated hybrid waveguide with the same geometrical parameters displayed in Figure 2e,f show overall qualitative agreement while differing quantitatively with respect to the plasmon modes. This is likely due to slight variations from the idealized sinusoidal shape assumed in the simulation. Remarkably, the absorption peaks of the PH$_h$ and PH$_s$ dispersion curves disappear near the predicted wavelengths and angles of the hybrid BICs of 860 nm and 2.9° as well as 887 nm and 4.6°, respectively. The analysis of the resonances around these points was performed by fitting a Lorentzian model (see the Experimental Section and Supporting Information) to the absorption spectra obtained by $A = 1 - R - T$. The fitting results, shown in Figure 2g,h, reveal an increase in the $Q$-factor up to the maximum observable value of the spectroscopy setup of 1300 (see Supporting Information) as well as a decrease in the absorption amplitudes to zero, which matches the theoretical predictions in the direct vicinity of a hybrid BIC. Together, these observations confirm the existence of hybrid BICs.

Since these states could be experimentally observed despite slight deviations of the plasmon resonances from the ideal simulated case, this is further interpreted as being a result of their topological protection. Most importantly, the excellent agreement of the $Q$-factor and absorption amplitude between the experiment and simulation lead to the conclusion that the observed hybrid BICs behave as predicted and visualized in Figure 1.

With the experimental proof of hybrid BICs, we then aim to theoretically analyze their potential performance. Although the FOM$^*$ of all BICs converge to infinity, this performance would require a light beam of vanishing momentum uncertainty that also requires infinite device size (space uncertainty). In practice, high radiance external light sources must be used to spectroscopically analyze the BIC proximity in energy-momentum space (see Figure 3a–c). Notably, this is why BIC research has focused on specular geometry to date (Figure 3a). In this geometry, the FOM$^*$ is calculated with respect to the reflection or transmission measured by a detector (Figure 3b). The schematic view of two coupled resonators (Figure 3c) shows why material losses substantially lower the FOM$^*$: the outgoing wave (the detected signal) arises from the coupling of the incident wave with the BIC-supporting coupled resonator system, leading to a spectral resonance. Additionally to the demands on the device size mentioned previously, toward an increasing radiative quality factor, the presence of material loss inevitably decreases the amplitude of the resonance and thus leads to a vanishing FOM$^*$ (see Supporting Information for mathematical details). However, for integrated optical applications, diffraction geometry (Figure 3d) appears more promising and utilizes the diffracted power emitted by a laterally excited mode (Figure 3e). It could, for example, be realized by an on-chip laser attached to a laterally structured hybrid BIC waveguide on top of a photosensitive detector region. The schematic representation of the diffraction geometry points to the reason why a higher FOM$^*$ can be obtained: here, the outgoing wave is directly coupled to the radiative component of the excited mode (Figure 3f). Toward the BIC, this radiative component is strongly altered and so is the corresponding FOM$^*$. This advantage of the diffraction mode is explored numerically in the following lines. Figure 3h visualizes dielectric BICs showing the same performance regardless of the geometry used, while this is remarkably different for hybrid BICs. To emulate the conditions of an integrated system with an internal light source, we assume that a propagating mode on the dispersion line of the PH$_h$ mode near the distinct frequency of the hybrid BIC is excited with an initial power of $P_{in}$, as emphasized in Figure 3e. We analyze its outcoupled diffracted power. As shown in the Supporting Information, the FOM$^*$ with respect to that outcoupled diffracted power can be approximated by the relative change of the radiative extinction rate

$$\text{FOM}^* = \frac{1}{\gamma} \frac{\partial \gamma}{\partial n}$$

and is visualized in Figure 3g, whereby the radiative extinction rate follows the proportionality $\gamma \propto 1/Q$. Notably, for a better comparison with the simulation results and experimental results from Figure 2, the FOM$^*$ is plotted against the light source wavelength $\lambda$ and outcoupling angle $\theta$ instead of the frequency and momentum. First, the FOM$^*$ is close to zero for all wavelengths and angles that do not fall together with the dispersion curves of the modes. This result is unsurprising since no guided mode solutions exist there. Along the dispersion curves of the modes,
the FOM$^*$ possesses somewhat higher values of about 263/RIU for the SPP modes and $\approx$ 1340/RIU for the PH modes for the majority of displayed wavelengths and angles. Most strikingly, toward the wavelength and outcoupling angle of the hybrid BIC at $\lambda_{BIC} = 860$ nm and $3^\circ$, we observe that the FOM$^*$ strongly increases to a value of more than $1.43 \times 10^5$/RIU and even surpasses the values expected for purely dielectric BICs$^{[45]}$ by nearly one order of magnitude. This result is due to the relative radiative $Q$-factor not decreasing in comparison to the purely dielectric case despite the presence of losses (see Supporting Information).

Simultaneously, the presence of surface plasmons increases the average sensitivity $S$, leading to an approximate relation

$$FOM^*_\text{hybr.} = \frac{1}{S} \frac{\partial \gamma}{\partial (\lambda - \lambda_{BIC})} S = \frac{Q_{\text{rad}}}{\lambda} S = FOM^*_{\text{diel.}} \cdot \frac{S}{S_{\text{diel.}}} \approx 8 \cdot FOM^*_{\text{hybr.}}$$  \(5\)

with $S_{\text{diel}}$ as the sensitivity of the PH$_x$ mode. This demonstrates that the hybridization of photons (high $Q$, low $S$) and plasmons (low $Q$, high $S$) does not lead to a simple averaging of the FOM$^*$ as known from other hybrid systems. For hybrid BICs, the radiative $Q$-factor $Q_{\text{rad}}$ is determined by the same high values of dielectric BICs regardless of how low the $Q$-factor of the plasmon is. This implies that hybridization improves performance by approximately one order of magnitude.

Until this stage, the enhanced FOM$^*$ is shown for the ideal case of plane wave irradiation for an infinite device size (Figure 3h). It might appear trivial that there is no advantage for hybrid BICs since a dielectric system also reaches infinite FOM$^*$. However, as previously stated, the device size $\Delta L$ and angular spread of the light source must be considered by a momentum spread $\Delta k$. The FOM$^*$ of a real system is approximated by the integral

$$FOM^*_\text{real} \approx \frac{1}{S_{\text{diel.}}} \frac{\partial \gamma}{\partial (\lambda - \lambda_{BIC})} S_{\text{diel.}}$$

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$$FOM^*_\text{real} \approx \frac{1}{S_{\text{diel.}}} \frac{\partial \gamma}{\partial (\lambda - \lambda_{BIC})} S_{\text{diel.}}$$
FOM\(^*\)(\(\Delta k\)) = \(\int G(k_{\text{el}}, \Delta k) \text{FOM}\(^*\)(k_{\text{el}}) \, dk_{\text{el}}\)  \(\text{(6)}\)

with \(G(k_{\text{el}}, \Delta k)\) as the Gaussian probability density function of width \(\Delta k\) in the \(k\)-space, as visualized by the blue curve in Figure 3h, leading to a finite FOM\(^*\) (see Supporting Information). For a parallel light source, the momentum spread can be expressed by \(\Delta k \approx 1/\Delta L\). A plot of this integrated FOM\(^*\) up to the propagation length (and thus the typical device dimension) of the hybrid waveguide of 80 \(\mu\)m shows that the FOM\(^*\) of the hybrid waveguide (D hybr.) remains superior to the dielectric one (D/S dieel.) for all device sizes (Figure 3i). At first sight, it appears unphysical that there is seemingly no trade-off with respect to material losses. In fact, there is a trade-off concerning the overall power consumption of a device as described in the Supporting Information. This trade-off, however, does not affect the strongly increased FOM\(^*\).

In conclusion, we have demonstrated the existence of hybrid photonic–plasmonic BICs fabricated using a cost-efficient fabrication method. From a practical perspective, the ability to produce hybrid waveguides of high symmetry on large scales opens up new opportunities for BICs in general and enables the production of transfer printable freestanding BIC waveguides, their combination with silicon substrates, 3D stacking for the realization of both complex and cost-efficient high FOM\(^*\) sensors and modulators. By using plasmonic materials with low plasmon frequencies, it is straightforward to adapt hybrid BICs to the telecommunication window. From a theoretical perspective, hybrid BICs in an integrated system enable substantially improved performance compared to dielectric BICs despite the introduction of a lossy material and—in contrast to conventional hybrid resonators—provide a new direction in the long-standing idea of enhancing photonics with hybrid systems. We further anticipate hybrid BICs for logical components with low energy consumption and ultrasensitive photonic devices with enhanced light-matter interaction utilizing active or nonlinear materials.

**Experimental Section**

**Sample Fabrication:** The approach to achieving freestanding hybrid waveguides is presented in Figure 5b of the Supporting Information. First, a glass substrate was coated by a functional layer of water-soluble polymer (PDAC) and a homogeneous layer of OrmoCore. The OrmoCore film was partially cross-linked at an exposure dose of \(\approx 10\%\) of the full film was partially cross-linked at an exposure dose of \(\approx 10\%\). Then, the entire stack was separated into two pieces. Using a commercially available sinusoidal stamp, the first piece was structured by UV-nanoimprint lithography and subsequently metalized. A sketch of the experimental setup for the optical characterization of the hybrid waveguide is presented in Figure 5c of the Supporting Information. A collimated helium–deuterium white light source was used as an illumination signal. To obtain angle-resolved measurements, both the sample and a grating spectrometer with a resolution of \(\Delta \lambda = 0.01\) nm were placed in a movable position on a 2-axis rotational stage independently from each other. All spectra were measured with an angular resolution of \(\Delta \theta = 0.075^\circ\).

**Q-Factor Extraction:** The \(Q\)-factors from Figure 2e,f were extracted by fitting a Lorentz model to the absorption spectra, which is described by

\[ A(\omega) = A_0 + \Delta A \frac{\gamma^2}{(\omega - \omega_0)^2 + \gamma^2} \]  \(\text{(7)}\)

where \(A_0(\omega)\) is a slowly varying continuous background and \(\Delta A\) is the absorption amplitude. \(\gamma\) defines the full width half maximum of the resonance and is linked to the \(Q\)-factor by \(Q = \omega_0/\gamma\). For further information see Supporting Information.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

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