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Nanometer-scale photon confinement inside dielectrics

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Optical nanocavities confine and store light¹–³, which is essential to increase the interaction between photons and electrons in semiconductor devices, enabling, e.g., lasers and emerging quantum technologies⁴–⁶. While temporal confinement has improved by orders of magnitude over the past decades, spatial confinement inside dielectrics was until recently believed to be bounded at the diffraction limit⁷–⁸. The conception of dielectric bowtie cavities (DBCs) shows a path to photon confinement inside semiconductors with mode volumes bound only by the constraints of materials and nanofabrication⁹–¹⁵, but theory was so far misguided by inconsistent definitions of the mode volume and experimental progress has been impeded by steep nanofabrication requirements. Here we demonstrate nanometer-scale photon confinement inside 8 nm silicon DBCs with an aspect ratio of 30, inversely designed by fabrication-constrained topology optimization¹³–¹⁶. Our cavities are defined within a compact device footprint of \(4\times10^2\) and exhibit mode volumes down to \(V = 3 \times 10^{-4} \lambda^3\) with wavelengths in the \(\lambda = 1550\) nm telecom band. This corresponds to field localization deep below the confinement limit in a single hotspot inside the dielectric. A crucial insight underpinning our work is the identification of the critical role of lightning-rod effects at the surface⁷–¹⁹. They invalidate the common definition of the mode volume, which is prone to gauge meretricious surface effects or numerical artefacts rather than robust confinement inside the dielectric. We use near-field optical measurements to corroborate the photon confinement to a single nanometer-scale hotspot. Our work enables new CMOS-compatibel device concepts ranging from few- and single-photon nonlinearities² over electronics-photonics integration²⁰ to biosensing²¹.

A wealth of mechanisms can be exploited for building nanocavities, including distributed Bragg reflection¹–³,²², total internal reflection²³, Fano resonances²⁴, plasmonic resonances²⁵, topological confinement²⁶, and bound states in the continuum²⁷. Common to existing approaches is that neither of them allow optical mode volumes, \(V\), in the deep subwavelength regime unless introducing absorption losses³,⁸. The underlying principle of DBCs is local field enhancements due to the electromagnetic boundary conditions across material interfaces⁹–¹₃,²₈–³₀. They demand that the tangential component of the electric field, \(E\), and the normal component of the displacement field, \(D = e\varepsilon\), are continuous. This implies that a semiconductor bridge surrounded by void features, cf. Figs. 1a and b, can confine light inside the material, which is crucial to enhance the interaction with embedded emitters³ or material nonlinearities¹². Besides the fundamentally different confinement mechanism, DBCs differ from previous cavity paradigms in several ways. First, the small mode volume of nanometer-scale DBCs implies strong light-matter interaction without resorting to extremely high quality factors, \(Q\), thus enabling applications requiring wide bandwidths such as nanoscale light-emitting diodes, few-photon nonlinearities¹², quantum optics with broadband emitters¹³, and optical interconnects²⁰. Second, the modes of DBCs are strongly confined and therefore very sensitive to the size of the dielectric bridge¹¹–¹₅ at the center of the bowtie. Smaller bridges reduce \(V\), immediately implying that a new frontier of nanocavities research is concerned with reducing the smallest feature size allowed by the nanofabrication process. This is in contrast to previous work that aimed to increase \(Q\), which required reducing structural disorder rather than the critical dimension³²,³³. Finally, the commonly used definition of the mode volume is not generally applicable to DBCs because it can pick up unintended surface effects rather than the effect of confining light inside the material, as discussed in further detail below and in Supplementary Section 1.

Inverse design and nanofabrication

We use carefully measured fabrication constraints as input to size- and tolerance-constrained topology optimization¹³,¹⁶ aiming to maximize the projected local density of optical states⁵ (LDOS) at the geometric center of the domain. Before running the optimization algorithm, we establish the smallest possible feature size of our nanofabrication process, see Supplementary Section 2. We fabricate 240 nm crystalline (100) silicon membranes \((n = 3.48)\) suspended in air using electron-beam lithography, dry etching, and selective vapour-phase hydrofluoric acid etching. We optimize a cyclic dry-etching process³⁴ to minimize the critical dimension while tolerating periodic sidewall roughness in the form of scallops, see Methods. We note that surface roughness and the size of the scallops could be reduced by hard etching masks. The fabrication constraints are quantified as a set of critical dimensions, which we define through minimum attainable radii. For our process, we find the radius of curvature of any solid feature, \(r_s \geq 10\) nm, and any void feature, \(r_v \geq 22\) nm. The critical radii are limited by proximity effects during electron-beam lithography but it is possible to go below these limits with manual shape modifications of the exposure mask, see Supplementary Section 3. From systematic tests we find that it is possible to obtain a mean bowtie bridge width of 8 nm in a localized area, which we include as a third critical radius of curvature, \(r_c \geq 4\) nm, at the center of the design domain. The topology optimization targets a maximum LDOS around \(\lambda = 1550\) nm by tailoring the material layout in a small square domain with \(2\times1\) side length.

We obtain the highly optimized DBC shown in Fig. 1a, which strongly enhances the vacuum field in the center of the cavity as shown in Fig. 1b, and calculate \(V \sim 0.08\) \((\lambda/(2\pi))^3\) and \(Q \sim 1100\), around \(\lambda = 1551\) nm. We fabricate DBCs based on these parameters and the resulting structures show excellent...
Fig. 1: Fabrication of topology-optimized silicon dielectric bowtie cavity (DBC). a, Rendering of the DBC design generated by tolerance-constrained topology optimization. The normalized $|E|$-field is projected on the faces defining the three geometry planes of the design. b, Zoom-in of the solid silicon bowtie exhibiting a strong field confinement due to the bowtie bridge dimension of 8 nm. c, 40° tilted scanning electron microscopy (SEM) image of a fabricated cavity. d, Global geometry-tuning, $\delta$. Each air (black) pixel (1 nm$^2$) inside a $\delta$-outline is exposed uniformly with electron-beam lithography; hence, air features defining the device are uniformly tuned. e–g, 40° tilted SEM images of bowtie region for $\delta = \{-2, -4, -6\}$ nm. We measure the mean width of the fabricated bowties to be $(8 \pm 5)$ nm, $(10 \pm 5)$ nm, and $(17 \pm 5)$ nm for figures e, f, and g, respectively, noting the variation in width along the z-direction caused by the scallops and $\sim 1^\circ$ negative sidewall angle represented by the uncertainty as discussed in the main text.

We calculate the quasi-normal mode of the structure shown in Fig. 1a (including the tethers used to suspend the cavity, cf. Fig. 1e) using a finite-element method and evaluate the effective mode volume

$$\frac{1}{V} = \text{Re} \left\{ \int_V e_\sigma(r) E^2(r) dV + i \frac{\sqrt{\varepsilon}}{2a} \int_S E^2(r) dA \right\}, \quad (1)$$

with $E(r)$ and $e_\sigma(r)$ the electric field and dielectric constant at position $r$, respectively. $\omega$ is the complex angular eigenfrequency of the cavity mode and $c$ is the speed of light. The mode volume is in general a function of position, but for this to be a robust and useful definition, we evaluate it at the center of the cavity, $r_0$. The volume integral is over the entire simulation domain, while the surface integral should be evaluated on the outer boundaries and in practical calculations only constitutes a minor correction for high-$Q$ cavities such as our DBCs.\textsuperscript{35}

Measuring the width of the fabricated silicon bridge is crucial for rigorously comparing theory and experiment for DBCs. However, the bridge width of a few nanometers is close to the practical resolution limit of conventional microscopy methods, such as scanning electron microscopy (SEM). We therefore fabricate three sets of DBCs, each of which subject to a global geometry-tuning, $\delta$, of the entire mask, thereby shrinking the exposed areas (air) in incremental steps of 2 nm as shown in Fig. 1d. In order to further validate the yield and reproducibility, we fabricate and characterize six nominally identical copies of each geometry-tuned device. Representative SEM images of each of the three geometry-tuned devices are shown in Figs. 1e–g and the 2 nm systematic variations are clearly observed in the change of the fabricated bowtie dimensions. We measure a mean bowtie width of 8 nm, 10 nm, and 17 nm, for the three geometry-tuned devices, respectively. See Methods and Supplementary Section 4 for further details on the SEM characterization, and Supplementary Section 7 for an overview of devices characterized in this work.

Far- and near-field measurements

We characterize the devices using confocal cross-polarized microscopy (see Methods) and a representative reflection spectrum is shown in Fig. 2a. This spectrum shows the cavity mode as a feature around 1520 nm. The DBC mode interferes with the low-$Q$ vertical cavity mode formed by the $(\sim 3 \mu m)$ air gap between the silicon device layer and the silicon substrate. This results in a Fano resonance, which is well known from confocal characterization of nanocavities.\textsuperscript{36} The Fano line shape takes the form

$$F(\omega) = A_0(\omega) + \frac{q + 2(\omega - \omega_0)/\Gamma}{1 + [2(\omega - \omega_0)/\Gamma]^2}, \quad (2)$$

where $\omega$ is the frequency, $\omega_0$ is the DBC resonant frequency, $\Gamma$ is the linewidth, $A_0(\omega)$ is a linear function representing the
background low-\(Q\) mode, \(q\) measures the relative amplitudes between the main and the background modes, and \(F_0\) is a constant scaling factor. The spectra for all six copies of each of the three geometry-tuned devices shown in Figs. 1e-g are displayed in Figs. 2b-d. We fit the Fano model locally around each resonance and extract \(\omega_0\) and the quality factor \(Q = \omega_0/\Gamma\) for all 18 devices of the three global geometry-tuning parameters. Figure 2e shows the mean and standard deviation of the resonant wavelength, \(\lambda_0\), and \(Q\), for each \(\delta\). We obtain a mean spectral shift \(\Delta \lambda = 0.21 \pm 0.06\) nm between each value of \(\delta = -2\) nm from a linear fit and find that the standard deviation of the resonance shift of each set of geometry-tuned devices is \(\leq 4 \pm 0.6\) nm. That is, the six nominally identical copies has spectral shifts \(\leq \Delta \lambda/10\), which corresponds to the devices being identical within \(|\delta| \leq 0.2\) nm.

While far-field measurements give important insights into the spectral properties of DBCs, they do not allow extracting information about the mode shape and confinement. We therefore interrogate the near-field immediately above the DBCs using a scattering-type scanning near-field optical microscopy (s-SNOM), where a continuous-wave laser is focused on an oscillating atomic force microscope (AFM) silicon tip scanning across the DBC. Figure 3a shows the measured topography, which provides a clear image of the device but also shows that the tip penetrates into the void features, implying that the measured geometry is convolved with the function describing the tip. For the near-field optical characterization we use a pseudo-heterodyne interferometric detection scheme, which strongly suppresses interference with the far-field background. This experiment allows recording the optical spectrum of the cavity mode without exciting the low-\(Q\) background resonance. Figure 3b shows the measured amplitude at an effective height of 5 nm above the surface at the center of the DBC. We model the measured cavity mode using a Green-tensor formalism treating the tip as a polarizable dielectric sphere and find that the measured amplitude is modulated by the intensity of the cavity mode. From a Lorentzian fit in the frequency domain we obtain \(\lambda_0 = (1489.4 \pm 0.1)\) nm and \(Q = 370 \pm 40\). The reduction in \(Q\) arises since the s-SNOM tip acts as an additional loss channel for the cavity so the s-SNOM experiment measures a loaded quality factor. See Supplementary Section 5 for further details.

When continuously exciting the DBC with a laser tuned to the cavity resonance while scanning the position, we can map out the spatial structure of the cavity mode. The result, which is shown in Fig. 3c shows that the mode is strongly localized at a single hotspot. The near-field measurements in Fig. 3c show enhanced fields at the edges of the void features on the sides of the silicon bridge. These scattering fields arise because the tip goes down into the holes and therefore scatters not only surface fields but a complex combination of the surface field and the field in the voids, see Supplementary Section 5. We disregard the data obtained when the tip falls into the voids in the following analysis to facilitate a direct comparison between the measured field above the device to theoretical predictions. Figure 3d shows a high-resolution map of the measured normalized scattered field amplitude with the regions above the voids blacked out. The measured field cannot be compared directly to the calculated quasi-normal mode shown in Figs. 1a-b because the measured amplitude probes the intensity of the cavity mode and, in addition, because of the influence of the tip. We model the tip instrument function, \(f(\sigma)\), as a Gaussian of standard deviation \(\sigma\) and maximize the overlap between measured and calculated field through the Bhattacharyya coefficient, \(\tau = \frac{\sum |E_\text{m}| \cdot (|E_\text{c}|^2 + f(\sigma))}{\sum |E_\text{m}|^2 + \sum |E_\text{c}|^2 + \sigma^2}\). The tip has a nominal radius of curvature of 10 nm and probes the field when the edge is 5 nm above the surface. Both fields are normalized, \(\sum |E_\text{m}| = \sum |E_\text{c}|^2 + f(\sigma) = 1\). This analysis yields \(\sigma = (37 \pm 5)\) nm and \(\tau = 0.984\) indicating an excellent agreement between theory and experiment. The instrument function is broader than the DBC mode size, so the measurement gives an upper bound to the mode volume. Notably, we find that the mode is confined to dimensions much smaller than 37 nm in agreement with our theoretical predictions. Additional s-SNOM measurements (see Supplementary Section 5) on a device of different global geometry-tuning, \(\delta = -6\) nm (corresponding to a mean bowtie width of 17 nm), also yields the largest overlap, \(\tau = 0.991\), for the same instrument function \(\sigma = 37\) nm. The overlap between the two measurements is \(\tau = 0.996\), which further confirms that the DBC mode is localized below the instrument.
with matter inside the material. In addition, it is well known that symmetries. This explains the seemingly small reported mode volumes stem from surface fields associated with broken
their experimental demonstration would require extremely careful if dielectric cavities relying on surface fields can be realized, combining Eq. (1) with cavities with a high degree of symmetry can lead to to a vanishing mode volume despite the Purcell factor
nanometer-scale dielectric defect placed far from the cavity center that the max-definition applied to a conventional L3 cavity with a
sensitive to, or even indistinguishable from, structural disorder. Experimentally, such surface effects are extremely
fields that are picked up by the max-definition, which therefore occurs inside the material so the two definitions are equivalent.
For DBCs, however, they are entirely different quantities. A DBC such as L3 or H1 photonic-crystal cavities
occurs inside the material so the two definitions are equivalent.

These experiments can therefore not be compared to our work on confinement of light to a single hotspot inside the dielectric, with the mode volume evaluated using a robust definition and carefully measured structural parameters of the actually fabricated and measured devices.

**Discussion and outlook**

Strongly confining light inside dielectrics, as opposed to in air, vacuum, or at material boundaries, is central to applications relying on enhancing the light-matter interaction. Our cavities enhance the light-matter interaction by a Purcell factor of 6 × 10^3 over a bandwidth of up to 2 nm. This large bandwidth is needed for nonlinear optics and optical interconnects and appears on purpose in our design due to the compact device footprint of 4 nm. Extending the design domain would result in much higher Q, and experiments have shown Q-factors in silicon photonic-crystal cavities up to 9 million. Our work therefore not only demonstrates unprecedented levels of photon confinement inside dielectrics (see Supplementary Section 6 for a detailed comparison to previous experimental work), it also paves the way for experiments in extreme regimes of light-matter interaction and enable experimental studies of fundamental limits to photon confinement. Such efforts will in turn require developing new optical characterization methods that address the new experimental challenges posed by the mode volume of DBCs falling below the resolution of characterization techniques such as SNOM or cathodoluminescence. Electron energy-loss spectroscopy may be a promising characterization method although the combination of polarization, wavelength, and device thickness pose significant challenges.
states\textsuperscript{5}, are even more challenging because quantum dots are generally substantially larger than the \SI{8}{nm} bridge we demonstrate here. Our work demonstrates the theoretical prediction\textsuperscript{10,11} that a direct integration of fabrication constraints in the inverse design process enables realizing complex nanostructures of dimensions which are unprecedented in both research and industry. We note that the technology nodes, such as the current "\SI{5}{nm}", of the semiconductor industry no longer describe the smallest features in integrated circuits defined by lithography\textsuperscript{46}. In fact, the current industry roadmap for lithography does not aim to go below \SI{8}{nm} before 2034. Our method is therefore unlocking new experimental regimes throughout most areas of semiconductor nanotechnology\textsuperscript{47}, including nanophotonics\textsuperscript{6}, cavity optomechanics\textsuperscript{48}, nanoelectromechanics\textsuperscript{49}, quantum photonics\textsuperscript{5}, and nanorobotics\textsuperscript{50}.

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Methods

The inverse design process

For the inverse design procedure we model the physics using Maxwell’s equations in a finite volume of space, assuming time-harmonic field behavior. We exploit the three-fold spatial symmetry of the DBC structure to reduce the model size and truncate
the modelling domain using symmetry conditions and first-order absorbing boundary conditions. The model is discretized and solved using the finite-element method with first-order Nedelec elements. The problem of designing a DBC is solved using topology optimization by recasting it as a continuous constrained optimization problem. In this process we select a subset of the model domain, i.e., the design domain, and introduce one spatially constant continuous design variable per finite element in the design domain. We apply a filtering and thresholding procedure to regularize the design. The filtered and thresholded design variables are linked to the model through a material interpolation scheme. Hereby, the design variables control the material distribution. The optimization problem is solved using the globally convergent method of moving asymptotes. For the domain considered in this work, we choose a fixed membrane thickness of 240 nm and restrict the design to only vary in the (x,y)−plane by linking the design variables along the z-direction. Before the design process is executed we specify the design domain, the minimum radii of curvature of the solid and void phases in the design as well as at the center, and further specify the target cavity-resonance wavelength and the position of the mode extremum in the cavity. Otherwise, we allow the design to emerge freely from the design process.

Fabrication processes
A 25-by-25 mm chip is cleaved from a silicon-on-insulator wafer with a 240 nm (100) device layer and a 3 μm buried oxide. It is cleaned sequentially with de-ionized water, acetone, isopropanol (IPA), and dried with dry N₂. The sample is dehydrated for 5 min at 200 °C and ~ 65 nm chemically semi-amplified resist (CSAR) is spin-coated from CSAR6200.04 (CSAR6200.09 diluted 1:1 in anisole) at 6000 rpm for 60 s followed by a 5 min softbake at 200 °C. Six nominally identical copies of the cavity layout (56 combinations of local mask corrections and global geometry-tuning) are exposed uniformly on a 100 kV 100 MHz JEOL-9500FSZ electron-beam writer with current I = 202 pA, dose D₀ = 3 μC nm⁻², and shot pitch, p = 1 μm. The samples are developed for 60 s in AR-600-546 (amyl acetate), cleaned in IPA, and dried with dry N₂ in an automatic Laurell EDC 650 paddle developer for high reproducibility. All devices are separated by 25 μm to avoid proximity effects. The patterns are transferred to the device layer with 10 cycles of a modified version of the CORE-sequence operated at +20 °C. This process is a low-power switched reactive ion etching process using SF₆ for the etch and oxygen for sidewall passivation, thus avoiding fluorocarbon residues. Specifically, we fine-tune the process to achieve an aspect ratio of 30 from the thin softmask required by lithography. To improve the mask selectivity we reduce the platen power of the R-step from 10 W → 8 W and to reduce sidewall erosion we increase the O-step (passivation) from 3 s → 4 s. Lastly, we reduce the SF₆ flow in the E-step from 15 sccm → 10 sccm, and modify the duration of this step from 73 s → 72 s. The resist is removed with 1165 Remover (N-Methyl-2-pyrrolidone) followed by IPA and dried with dry N₂. The sample is then cleaned for 10 min in a Teplα 300 barrel asher with 400 sccm O₂-flow and 70 sccm N₂-flow at 1 kW with a maximum temperature of 72 °C. The buried oxide is etched in anhydrous hydrofluoric acid (99.995 %) using ethanol as catalyst at a process pressure 131 Torr in an SPTS Primaxx Uetch enabling both pressure and temperature control throughout the release. The sample is baked for 5 min at 200 °C prior to the release etch to avoid residues.

Scanning electron microscope characterization
We measure the dimensions of the fabricated structures by comparing a combination of top-view and tilted SEM images analyzed with detailed image analysis, presented and discussed in Supplementary Section 4. We measure the width of the bowties as 13 nm, 15 nm, and 21 nm from the top-view SEM images of the 3 sets of devices presented in Fig. 1a−g, respectively. Furthermore, we use multiple tilted views to estimate the width at the bottom of the bowties, which we find is ~ 10 nm narrower than at the top. This implies a negative sidewall angle ~ 1° of all devices and a mean width of the bowtie bridges of 8 nm, 10 nm, and 17 nm, for the three geometry-tuned devices, respectively, consistent with the critical radius of curvature imposed on the topology optimization. Supplementary Section 1 presents careful numerical simulations of the fabricated dimensions, which both includes the sidewall angle as well as variations of the dimensions of the calculated structure. This confirms that the mode volume in the center of our tolerance-constrained DBC-design remains robust to variations and is deep below the diffraction limit.

Confocal cross-polarized microscopy setup
A supercontinuum laser (NKT Photonics SuperK Compact) is focused on the through the cavity through the same objective and measured with an optical spectrum analyzer (AQ6370D Yokogawa), wavelength range λ = [1200, 1700]nm. The excitation polarization is controlled with a λ/2-plate and light is collected through a linear polarizer rotated 90° to reduce specular reflections. Both excitation and collection is rotated 45° to the main optical axis of the cavity (along x in Fig. 1a).

Near-field optical measurements
We use an s-SNOM (Neaspec, neaSNOM), equipped with a pseudo-heterodyne module, in reflection mode to map the DBC modes in the near-field. The incident light from a tunable continuous-wave laser (Santec, TSL-710) is focused on a silicon AFM probe (NanoWorld, Arrow-NC) with a nominal tip radius of 10 nm. The probe is used in intermittent contact mode at a frequency f₀ = 280 kHz oscillating with an amplitude of 60 nm. The amplitude of the scattered signal depends nonlinearly on the height above the sample due to the near-field contribution, therefore, demodulating at 4f₀ with a lock-in amplifier yields the near-field signal at the smallest height (~ 5 nm) above the surface while strongly suppressing contributions from the far-field background. The laser is s-polarized, which is aligned along the x-axis of the DBC (see Fig. 1a), to minimize the perturbation from the tip and to excite the cavity most efficiently. A polarizer is placed in front of a photoreceiver (New Focus, 2053-5S) to select the s-polarization of the scattered field. We determine the resonant wavelength in the near-field from a Lorentzian fit to the near-field spectrum obtained from a fixed position in several spatial maps obtained around the bowtie for a number of wavelengths in a 20 nm band, see Supplementary Section 5 for further details.

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Author contributions

S.S. and J.M. initiated and supervised the project. M.A., supervised by B.V.L and S.S., developed the lithography concepts, fabricated the sample, performed SEM characterization, far-field optical characterization, and most of the data analysis. V.T.H.N. and H.J. developed the dry-etching process. R.E.C. and O.S. developed and carried out the topology optimization. L.N.C. and N.S. performed the near-field measurements. M.A., B.V.L., R.E.C., S.E.H., L.N.C., N.S., O.S., J.M., and S.S. contributed to data analysis, discussions, and preparation of figures. M.A., B.V.L, and S.S. wrote the manuscript with contributions and input from all authors.

Data availability

Data is available upon reasonable request.

Competing financial interests

The authors declare no competing financial interests.
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