

Near infrared salinity sensing with an asymmetric silicon nanodisk dimer metasurface

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Research Article

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Abstract

Optical salinity sensing needs a transducer whose spectrum changes predictably with the refractive index of the water. We simulate a near infrared metasurface made of two unequal silicon nanodisks (radii 180 and 170 nm, height 280 nm, gap 80 nm) on fused silica and immersed in saline water. Three-dimensional finite difference time domain calculations were run at 0, 10, 20, 30, 40, and 50 ppt with the index relation $n = 1.3330 + 1.7 \times 10^{-4}S$. The transmission spectrum contains one narrow dip with a Fano line shape that moves from 1567.47 to 1571.33 nm. A linear calibration gives 77.10 ± 0.10 pm/ppt (95% confidence interval), or 453.5 ± 0.6 nm/RIU, and the slope changes by less than 0.2 pm/ppt when the dip is located in seven different ways. The half depth width falls from 2.57 to 2.51 nm, which gives Q between 610 and 626 and a figure of merit between 177 and 181 RIU^{-1} ; Q moves by about 4% depending on the baseline used for the half depth. Read at a fixed wavelength on the steepest flank, the transmission changes by 4.7 to 4.95 percentage points per ppt. Near field exports at 0 and 50 ppt are included for reference, but they were recorded at 1530 and 1590 nm and not at the dip, so they are not used to assign the resonance. Estimates from seawater optics indicate that a 1 K temperature change mimics 0.5 to 0.7 ppt, so a practical device needs a temperature reference.

Highlights

- Asymmetric silicon dimer metasurface shifts its transmission dip by 77.10 pm/ppt of salinity
- Slope varies by less than 0.2 pm/ppt across seven ways of locating the dip
- Half depth width of 2.5 nm gives Q of 610 to 626; Q moves 4% with baseline choice
- At a fixed wavelength, transmission changes by up to 4.95 points per ppt
- Temperature (0.5 to 0.7 ppt per K) is the largest uncontrolled error term

1. Introduction

Salinity decides whether water can be used for drinking, irrigation, or aquaculture. In low lying deltas such as coastal Bangladesh, saltwater intrusion is already cutting into agricultural output [1], and monitoring it cheaply over large areas is a practical problem. Conductivity probes are the standard tool, calibrated against the Practical Salinity Scale and now usually reported as Reference or Absolute Salinity [2]. Reading salinity from the refractive index of the water is an alternative that needs no electrodes and can be done remotely through a window or a fiber. Fiber sensors built on interferometers, gratings, and plasmonic coatings have been developed along these lines and reviewed [3,4]; a polyimide coated photonic crystal fiber in a Sagnac loop, for instance, responds with 0.742 nm per mol/L of NaCl and includes a temperature channel [5].

A planar metasurface could do the same job in a much smaller footprint. High index dielectric nanostructures support strong electric and magnetic Mie resonances with little intrinsic loss [6,7], and resonant nanophotonic devices are now routine as label free sensors [8–10]. For bulk refractive index sensing the useful numbers are the shift per refractive index unit, the linewidth, and the figure of merit that combines them [11].

Narrow lines are easiest to obtain from bound states in the continuum. A bound state in the continuum is a localized mode that sits inside the radiation spectrum but cannot couple to it [12,13]; it has been observed in photonic structures [14]. Breaking the symmetry that protects the mode opens a radiative channel whose strength is set by the asymmetry, and the mode becomes a quasi-bound state with a finite, tunable linewidth [15,16]. The line shape that results are usually described with the Fano formula for interference between a narrow and a broad channel [17–19].

Quasi bound state metasurfaces have been used as refractive index sensors in crescent, nanohole, nanogap, detuned particle, and dual resonance geometries [20–27]. Measured sensitivities run from a few tens to several hundred nm/RIU; a dual nanohole silicon device gave 79.8 and 38.3 nm/RIU in its two bands [25], and one recent paper collects values from 86.7 to 657 nm/RIU for this class [24]. Almost all of this work is calibrated with index matching liquids. Salinity enters rarely, and the complications that come with water, namely temperature, dispersion, and absorption near 1.5 μm , are seldom discussed [28–30], even though temperature cross sensitivity is a known weakness of quasi bound state sensors [31] and the main design issue for fiber salinity probes [4].

Here we examine one deliberately plain structure, two circular silicon disks whose radii differ by 10 nm, and ask what its simulated spectra say about salinity sensing. We locate the resonance with a line shape fit instead of the sampled minimum, test how much the calibration depends on that choice, evaluate fixed wavelength readout directly from the simulated spectra, and estimate the water related errors that the simulation leaves out. We also include the near field exports available at 0 ppt, with their true monitor wavelengths. We do not claim a record Q, and we do not claim that the resonance is a bound state in the continuum; what would be needed to show that is listed in Section 4.4.

2. Device and numerical method

2.1. Geometry and materials

The unit cell (Fig. 1, Table 1) holds two silicon cylinders side by side along x on a fused silica substrate. The larger disk has radius $R_1 = 180$ nm and the smaller $R_2 = 170$ nm, both are 280 nm tall, and the edge-to-edge gap is 80 nm. The lattice is rectangular with periods $P_x = 1000$ nm and $P_y = 800$ nm. The relative radius difference, $(R_1 - R_2)/R_1 = 0.056$, is the only intentional symmetry breaking. Silicon and silica are treated as lossless and constant in wavelength, with indices 3.48 and 1.45. Tabulated values near 1.55 μm are close to these [32,33]; the Sellmeier fit of Malitson gives 1.444 for silica at 1.57 μm , so the value

used here is about 0.006 high. Light arrives at normal incidence from the water side and transmission is recorded in the substrate.

Table 1
Structural and numerical parameters of the model.

Parameter	Symbol	Value
Larger disk radius	R_1	180 nm
Smaller disk radius	R_2	170 nm
Disk height	h	280 nm
Edge to edge gap	g	80 nm
Period along x	P_x	1000 nm
Period along y	P_y	800 nm
Silicon index	n_{Si}	3.48 (constant)
Fused silica index	n_{sub}	1.45 (constant)
Analyte index	$n(S)$	Eq. (1)
Spectral window	λ	1530 to 1590 nm, 3001 points (0.02 nm step)

2.2. Simulation

Calculations were done with a three-dimensional finite difference time domain solver (Ansys Lumerical FDTD) [34]. Boundaries were periodic along x and y and absorbing along the propagation direction. A plane wave illuminated the structure from the analyte side, and transmission was sampled at 3001 wavelengths from 1530 to 1590 nm. Geometry and numerical settings were the same for every salinity, so differences between spectra come only from the analyte index. Field monitors recorded the electric field, magnetic field, and Poynting vector in the XY plane at $z = -304$ nm and in the YZ plane at $x = 0$, for 0 and 50 ppt; their wavelengths are given with each figure, and Section 3.5 explains why they matter.

2.3. Salinity to index relation

The index of the saline water was set to

$$n(S) = 1.3330 + 1.7 \times 10^{-4} S \quad (1)$$

with S in parts per thousand. We checked the constants against the empirical seawater equation of Quan and Fry [28], and formulations that add pressure dependence give the same picture at the surface [35]. For pure water at 589 nm and 20°C that equation returns 1.33301, so the baseline in Eq. (1) is the visible wavelength value. Its salinity coefficient evaluated at 1570 nm is 1.70×10^{-4} per ppt at 20°C and

1.69×10^{-4} per ppt at 25°C, which supports the slope used here. Two cautions apply. The Quan and Fry equation was fitted to visible data, and measured pure water indices near 1.55 μm lie around 1.32 [29,30], about 0.01 to 0.015 below the baseline. The relation also assumes sea salt composition, so salinity here means the mass fraction of dissolved sea salt in parts per thousand, and Reference Salinity is 1.004715 times Practical Salinity [2]. Section 4.2 follows up on the baseline offset.

2.4. Spectral analysis

The transmission dip was fitted in a window of ± 6 nm around the sampled minimum with

$$T(\lambda) = T_0 + A [(q + \varepsilon)^2 / (1 + \varepsilon^2) - 1] \quad (2)$$

where $\varepsilon = 2(\lambda - \lambda_0)/\gamma$, q is the asymmetry parameter, γ the linewidth parameter, and T_0 and A the baseline and amplitude [17,18]. The dip wavelength λ_{dip} is the minimum of the fitted curve on a 0.0001 nm grid, which removes the 0.02 nm sampling limit. Sensitivity to salinity, sensitivity to index, quality factor, and figure of merit are

$$S_S = \Delta\lambda_{\text{dip}} / \Delta S \quad (3)$$

$$S_{\text{RI}} = \Delta\lambda_{\text{dip}} / \Delta n \quad (4)$$

$$Q = \lambda_{\text{dip}} / \text{FWHM} \quad (5)$$

$$\text{FOM} = S_{\text{RI}} / \text{FWHM} \quad (6)$$

with Δ taken from a least squares line over 0 to 50 ppt. The FWHM is the width at half depth of the sampled dip, measured from the off-resonance level to the minimum with linear interpolation between samples; the off-resonance level is the largest transmission within ± 30 nm of the dip unless stated otherwise. A wavelength uncertainty $\delta\lambda$ corresponds to a salinity uncertainty

$$\delta S = \delta\lambda / S_S \quad (7)$$

before temperature and other systematic effects are included. For intensity readout we use

$$\text{FOM} = \max | \partial T / \partial n | / T^* \quad (8)$$

which grows without limit as T approaches zero, so it is quoted with a transmission threshold. Confidence intervals of regression slopes are 95% intervals from Student statistics with four degrees of freedom (six points).

3. Results

3.1. Transmission spectra

Away from the resonance the transmission is 0.95 at 1530 nm and about 0.98 near 1580 nm (Fig. 2a). A single narrow dip appears at 1567.47 nm for pure water. Its minimum transmission is 0.0093, it is 0.0021 at 30 ppt, and it reaches zero within numerical accuracy at 40 and 50 ppt. Raising the salinity moves the dip to longer wavelength and creates no other feature in the window. The fitted dip wavelengths are 1567.470, 1568.239, 1569.009, 1569.780, 1570.552, and 1571.325 nm for 0, 10, 20, 30, 40, and 50 ppt, a total red shift of 3.855 nm (Table 2). The asymmetry parameter is small and positive, $q = 0.163$ to 0.169 (Table 3), so the dip is nearly symmetric with a shoulder on its short wavelength side. The fits describe the sampled spectra with $R^2 \geq 0.99997$ in the fitting window.

Table 2
Resonance metrics. Dip wavelength from the Fano fit; FWHM, Q, and FOM from Eqs. (5) and (6) with $S_{RI} = 453.5$ nm/RIU.

S (ppt)	<i>n</i> (RIU)	λ_{dip} (nm)	$\Delta\lambda$ (pm)	FWHM (nm)	Q	FOM (RIU ⁻¹)	<i>T</i> _{min}
0	1.3330	1567.470	0	2.569	610.2	176.5	0.0093
10	1.3347	1568.239	769	2.568	610.6	176.6	0.0070
20	1.3364	1569.009	1539	2.550	615.3	177.8	0.0046
30	1.3381	1569.780	2310	2.535	619.4	178.9	0.0021
40	1.3398	1570.552	3082	2.520	623.1	179.9	≈ 0
50	1.3415	1571.325	3855	2.509	626.4	180.8	≈ 0

Minimum transmission values of -3×10^{-5} (40 ppt) and -0.0018 (50 ppt) are numerical artifacts of the time domain calculation and are listed as approximately zero.

Table 3
Fano fit parameters in a ± 6 nm window around each dip. $Q_F = \lambda_0/\gamma$.

S (ppt)	λ_0 (nm)	<i>q</i>	γ (nm)	<i>Q_F</i>	<i>R</i> ² of fit
0	1567.669	0.163	2.447	641	0.999986
10	1568.438	0.164	2.430	645	0.999979
20	1569.208	0.165	2.414	650	0.999979
30	1569.979	0.166	2.399	654	0.999984
40	1570.752	0.168	2.384	659	0.999989
50	1571.525	0.169	2.369	663	0.999990

3.2. Calibration and its dependence on the extraction method

A least squares line through the six dip wavelengths has a slope of 77.10 ± 0.10 pm/ppt (Fig. 3a) and R^2 above 0.99999. With the index step of 1.7×10^{-4} per ppt this is $S_{RI} = 453.5 \pm 0.6$ nm/RIU; the index step is an assumption of the model and carries no uncertainty here. Residuals stay within 1.8 pm with an RMS of 1.25 pm (Fig. 3b); the 30 ppt dip lies 1.7 pm below the value predicted by a line fitted to the other five salinities. The local slope between neighboring salinities creeps up from 76.92 pm/ppt (0 to 10 ppt) through 77.00, 77.08, and 77.20 to 77.31 pm/ppt (40 to 50 ppt), a rise of 0.5%, so the response is close to linear with weak positive curvature. These statistics describe a deterministic simulation under an imposed index law. They are not an experimental accuracy.

Because the slope is the quantity an experimenter would compare, we checked how much it depends on how the dip is located (Table 4). Fano fits in windows of ± 4 , ± 6 , and ± 10 nm, and the same fit on a spectrum thinned to 0.10 nm spacing, agree within 0.01 pm/ppt. A symmetric Lorentzian, a parabola through the bottom 0.7 nm of the dip, and the sampled minimum give 77.06, 77.10, and 77.26 pm/ppt. The spread across all seven variants is 0.2 pm/ppt, or 0.25%. The sampled minimum has the widest confidence interval (± 0.43 pm/ppt) because of grid quantization, which is why we use the fit.

Table 4
Calibration slope for seven ways of locating the dip. The last column is the largest change of any dip wavelength relative to the baseline Fano fit.

Extraction variant	Slope (pm/ppt), 95% CI	Max shift of λ_{dip} (pm)
Fano, window ± 6 nm (baseline)	77.10 ± 0.10	0.0
Fano, window ± 4 nm	77.09 ± 0.10	0.5
Fano, window ± 10 nm	77.10 ± 0.10	0.3
Fano, ± 6 nm, grid thinned to 0.10 nm	77.10 ± 0.10	0.0
Lorentzian, ± 6 nm	77.06 ± 0.10	205.9
Parabola on bottom ± 0.35 nm	77.10 ± 0.03	11.8
Sampled minimum (0.02 nm grid)	77.26 ± 0.43	10.0

The Lorentzian offset reflects the difference between the center of a symmetric model and the minimum of an asymmetric dip, not a fitting error.

The absolute dip position is less forgiving than the slope. The Lorentzian center lies up to 0.21 nm from the Fano minimum and the parabola up to 12 pm. These are differences of definition and not errors, but they mean that an absolute wavelength can be compared with an experiment only if both are analyzed the same way, whereas the slope in pm/ppt can be compared directly.

3.3. Linewidth, quality factor, and figure of merit

The half depth width shrinks from 2.569 nm at 0 ppt to 2.509 nm at 50 ppt, a drop of 2.4% (Fig. 4a), and Q rises from 610.2 to 626.4. Since S_{RI} comes from one global fit, the figure of merit simply follows the inverse linewidth, from 176.5 to 180.8 RIU^{-1} (Fig. 4b). The Fano linewidth γ narrows in the same way, from 2.447 to 2.369 nm (Fig. 4c), and gives somewhat higher quality factors ($Q_F = 641$ to 663) because it is defined by the fitted line shape and not by the half depth crossing. A weaker radiative coupling as the contrast between disks and water falls would explain the narrowing, but we have not tested that.

Q depends on the baseline chosen for the half depth. With the off-resonance level taken as the local maximum, as in Table 2, Q runs from 610 to 626. Taking the mean of the two band edge transmissions as the baseline gives 625 to 642, and taking unity gives 597 to 618. A spread of about 4% is therefore attached to any Q quoted here, and the baseline should be stated whenever Q is compared with another work.

The values are modest next to optimized quasi bound state designs. The radius difference of 5.6% was fixed in this study. For symmetry broken resonances the radiative quality factor is expected to scale as the inverse square of the asymmetry [15], so a sweep toward smaller differences is the obvious way to higher Q , at the cost of shallower dips and tighter fabrication tolerance. That sweep was not run.

3.4. Differential transmission and fixed wavelength readout

Figure 5a stacks the six simulated spectra against salinity, and Fig. 5b shows each spectrum minus the 0 ppt spectrum. Relative to pure water, the largest drop in transmission is 0.44 at 10 ppt, 0.72 at 20 ppt, 0.86 at 30 ppt, 0.93 at 40 ppt, and 0.96 at 50 ppt, while the largest rise, on the short wavelength side, is 0.30, 0.52, 0.66, 0.74, and 0.79. Only the six simulated curves are drawn; nothing is interpolated between salinities.

If the transmission is read at one wavelength, no spectrometer is needed. The steepest slope of each simulated spectrum is 0.613, 0.625, 0.632, 0.636, 0.639, and 0.642 per nm for 0, 10, 20, 30, 40, and 50 ppt (Fig. 6b). With the calibration slope, that corresponds to 4.73 to 4.95 percentage points of transmission per ppt for small changes at the best wavelength, and a transmission resolution of 1% would resolve about 0.2 ppt there. The steepest point moves with the dip, from 1568.22 nm at 0 ppt to 1572.06 nm at 50 ppt, so a single laser wavelength sits on the steep flank only over a limited salinity window. The intensity figure of merit of Eq. (8) is $2.2 \times 10^3 RIU^{-1}$ when only transmission above 0.10 is admitted and $4.9 \times 10^3 RIU^{-1}$ above 0.02, obtained by multiplying the measured spectral slope by S_{RI} (that is, assuming the dip shifts rigidly); it is an order of magnitude larger than the bulk figure of merit but depends on the threshold and on detector noise at low signal.

Figure 6a shows what this means at four fixed wavelengths. At 1570.1 nm the six sampled values are 0.89, 0.78, 0.51, 0.07, 0.11, and 0.41 for 0, 10, 20, 30, 40, and 50 ppt. The calibration line puts the dip center at 1570.1 nm near 34 ppt, and the two samples on either side of that salinity (30 and 40 ppt) are indeed the lowest, so the reading passes through a minimum there and rises again; the response is

ambiguous beyond that salinity unless a second wavelength is used. At 1569.4 nm the values fall from 0.79 to 0.10 between 0 and 20 ppt and reach 0.08 at 30 ppt, near the 25 ppt where the line crosses that wavelength. Because only six salinities were simulated, the dashed lines in Fig. 6a connect the sampled points and are not predictions between them. Intensity readout also inherits source power drift and any change in water absorption (Section 4.2).

3.5. Near field at 0 ppt

Field monitors were exported for 0 ppt in the YZ plane through $x = 0$ and in the XY plane at $z = -304$ nm. The solver records the wavelength in the file header, and for these exports it is 1590 nm for the YZ maps and 1530 nm for the XY maps. Both are far from the dip at 1567.47 nm, where the transmission is 0.97 and 0.95. The maps in Fig. 7 therefore show the near field of the structure off resonance, and we do not use them to describe the resonant mode.

Even so, the YZ map is informative. The field $|E|$ along the line $y = 0$ has two maxima, 4.30 at $z = 38$ nm and 4.59 at $z = 242$ nm, with a valley of 3.94 at $z = 128$ nm between them (Fig. 8b), and across y the peak at $z = 242$ nm is about 215 nm wide at half height above the lateral minimum. The magnetic field maximum, 0.0105, sits near $z = 128$ nm, which is where the electric field has its valley, and the Poynting vector peaks at 0.042 near $y = 0$, $z = 80$ nm. The XY map in the substrate is nearly flat, with $|E|$ between 0.85 and 1.10 times the source amplitude. Repeating these monitors at 50 ppt, with the same wavelengths, changes the XY electric field by at most 0.058 (5.9% of its mean) and the magnetic field by at most 3.8%. Along $y = 0$ in the YZ plane the two maxima grow to 4.48 and 4.88, which is 4.2% and 6.3% more than in pure water, and the valley is unchanged at 3.94. The off resonance field therefore responds weakly and smoothly to the analyte index.

4. Discussion

4.1. Context with published sensors

Table 5 sets the present numbers beside a few published ones. The entries differ in measurand, geometry, and method, so they indicate magnitude and are not a ranking. The simulated bulk sensitivity of 454 nm/RIU lies inside the range of 86.7 to 657 nm/RIU collected for bound state sensors [24] and above the measured values of the dual nanohole device [25]. The salinity response of 77.1 pm/ppt exceeds that of the fiber interferometer [5] once its molar sensitivity is converted using about 58 g/L per mol/L of NaCl, which gives roughly 13 pm per g/L; this compares a simulation with an experiment and should be revisited with measurements. A metasurface offers a planar footprint and a shift tied directly to the index of a thin liquid layer. It does not bring the temperature channel that the fiber probe includes [4,5].

The sensitivity can also be set against a physical limit. The normalized sensitivity is $S_{\text{RI}}/\lambda_{\text{dip}} = 0.289 \text{ RIU}^{-1}$. In first order perturbation theory the relative shift equals the fraction η of electric energy residing in the

analyte times $\Delta n/n_a$, so $\eta = 0.289 \times 1.333 = 0.39$ (0.38 for $n_a = 1.318$), compared with 0.75 RIU^{-1} for complete overlap. About 39% of the modal energy would then sit in the water, a large share for a high index resonator. This is an inference from the sensitivity and not a field calculation, and fields at the dip wavelength are needed to confirm it. Exposing more of the field, for example with gap or hole geometries [22], is the direct way to higher sensitivity.

Table 5

Context for the present sensitivity. Values are as reported by the cited works except were converted as noted.

Ref.	Platform	Measurand	Reported response	Basis
[25]	Silicon dual nanohole quasi-BIC metasurface	Bulk index, liquids 1.40 to 1.60	79.8 and 38.3 nm/RIU (two bands)	Experiment
[24]	Range collected for bound state sensors	Bulk index	86.7 to 657 nm/RIU	Literature summary
[5]	Polyimide coated photonic crystal fiber, Sagnac interferometer	NaCl concentration	0.742 nm per mol/L (about 13 pm per g/L)	Experiment
This work	Asymmetric silicon nanodisk dimer	Salinity, 0 to 50 ppt	77.1 pm/ppt (454 nm/RIU)	Simulation

4.2. Errors a real measurement would add

Table 6 lists what the simulation omits, with sizes estimated from the cited models. Two items need comment. The first is the baseline offset. The simulated index is the visible value, so in real water near $1.57 \text{ }\mu\text{m}$ the dip would lie at shorter wavelength by $S_{\text{RI}}\Delta n$, which is 4.5 to 6.8 nm for $\Delta n = -0.01$ to -0.015 . To first order the slope is unchanged, but the dip moves inside the 1530 to 1590 nm window and a final design should be recentered with measured water data [29,30].

The second is temperature. The Quan and Fry equation, extrapolated to 1570 nm, gives dn/dT between -8.3×10^{-5} and $-1.1\times 10^{-4} \text{ K}^{-1}$ for 0 to 35 ppt at 20 to 25°C. At the simulated S_{RI} that is a drift of 38 to 51 pm/K, equal to 0.5 to 0.7 ppt per kelvin. To hold 0.1 ppt, temperature must be known to about 0.15 to 0.2 K. Combining a 10 pm wavelength precision (0.13 ppt) with a 0.3 K temperature uncertainty (0.18 ppt) in quadrature gives 0.22 ppt, so beyond about 30 pm of wavelength precision the temperature term, not the spectrometer, sets the resolution. Silicon has its own thermo optic response of opposite sign that we did not simulate [32]. Fiber probes handle temperature with a separate channel [4,5], and a metasurface would need a reference device or a nearby thermometer. These temperature figures extrapolate a visible range equation and should be replaced by measured values at $1.57 \text{ }\mu\text{m}$.

Table 6
Effects not included in the simulation.

Factor	Estimated effect	Basis	Action
Water index at 1.57 μm below 1.3330	Dip moves 4.5 to 6.8 nm shorter; slope nearly unchanged	[28–30]	Rerun with tabulated water index
Water temperature	$dn/dT - 8.3 \times 10^{-5}$ to -1.1×10^{-4} K^{-1} : 38 to 51 pm/K, 0.5 to 0.7 ppt/K	Equation extrapolated to 1570 nm [28]	Temperature reference channel
Silicon thermo optic effect	Opposite sign shift, not simulated	[32]	Include in model; measure
Water absorption	Absorption coefficient of order 10 cm^{-1} near 1.55 μm : about 10% loss in 100 μm of water	[29,30]	Fluid layer of 100 μm or less; monitor power
Material dispersion and loss	Silicon and silica treated as constant; silica index 0.006 high	[32,33]	Use dispersive data
Numerical convergence	Slightly negative transmission at 40 and 50 ppt; 20 pm sampling	This work	Mesh and decay time study
Fabrication	10 nm radius difference is comparable to lithography tolerance; response to size error not simulated	This work	Tolerance sweep

4.3. Salinity definition and sample composition

Eq. (1) assumes the ionic mix of sea salt. Estuarine and river water in coastal Bangladesh blends sea salt with freshwater of variable composition, so the optical response per unit of conductivity or dissolved mass will differ between samples. Practical, Reference, and Absolute salinity differ by about 0.5% at open ocean composition [2], small next to the terms in Table 6 but worth stating when instruments are compared. Calibration against a conductivity reference on real samples belongs in any experimental validation [3].

4.4. What the data do and do not establish

The narrow Fano like dip of an asymmetric dimer is what the quasi-bound state design principle predicts [15], but the present simulations do not prove that origin. A convincing assignment needs a calculation at $R_1 = R_2$ in which the resonance disappears, a sweep of the radius difference showing the expected growth of linewidth, field maps at the dip wavelength (1567.47 nm for pure water) in the gap plane and at mid height of the disks, and a multipole decomposition of the radiating channels [16,25]. The field exports we have are at 1530 and 1590 nm, and a third file, a mode profile recorded at 1559.4 nm, is a normalized profile near unity everywhere and carries no resonance information, so we left it out. Section

3.5 is therefore reference material and not evidence for the mode. Dependence on polarization and incidence angle, and the effect of a finite array, also remain to be examined.

4.5. Route to experiment

The geometry has no holes or slots. It could be patterned by electron beam lithography and dry etching of a silicon film of about 280 nm on fused silica, followed by a thin fluidic cell. Deposited silicon will have optical constants different from the 3.48 assumed here and needs to be characterized. A tunable laser with a photodiode or a broadband source with a high-resolution spectrometer could read the response, and the first option can use the intensity route of Section 3.4 if source power is monitored. Calibration should combine saline standards, a conductivity reference, and a temperature-controlled stage.

5. Conclusions

A simulated asymmetric silicon nanodisk dimer shifts its near infrared transmission dip from 1567.47 to 1571.33 nm as salinity rises from 0 to 50 ppt under an index law checked against the Quan and Fry equation. The calibration slope is 77.10 ± 0.10 pm/ppt (453.5 ± 0.6 nm/RIU) and stays within 0.2 pm/ppt across seven ways of locating the dip. The half depth width of 2.57 to 2.51 nm gives Q of 610 to 626, with about 4% uncertainty from the baseline definition, and a figure of merit of 177 to 181 RIU⁻¹. Read at a fixed wavelength the transmission changes by up to 4.95 percentage points per ppt.

The simulation is nondispersive and isothermal. Estimates from seawater optics suggest that temperature alone shifts the dip by 38 to 51 pm/K, equal to 0.5 to 0.7 ppt per kelvin, and that the visible wavelength baseline puts the simulated dip 5 to 7 nm from where it would sit in real water. The near field exports at 0 and 50 ppt were taken off resonance and show a weak, smooth response to the analyte. Before experiments, the design needs a dispersive rerun, convergence tests, the symmetric limit with an asymmetry sweep, field maps and multipole analysis at the dip wavelength, a temperature reference, and a fabrication tolerance study.

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Figures

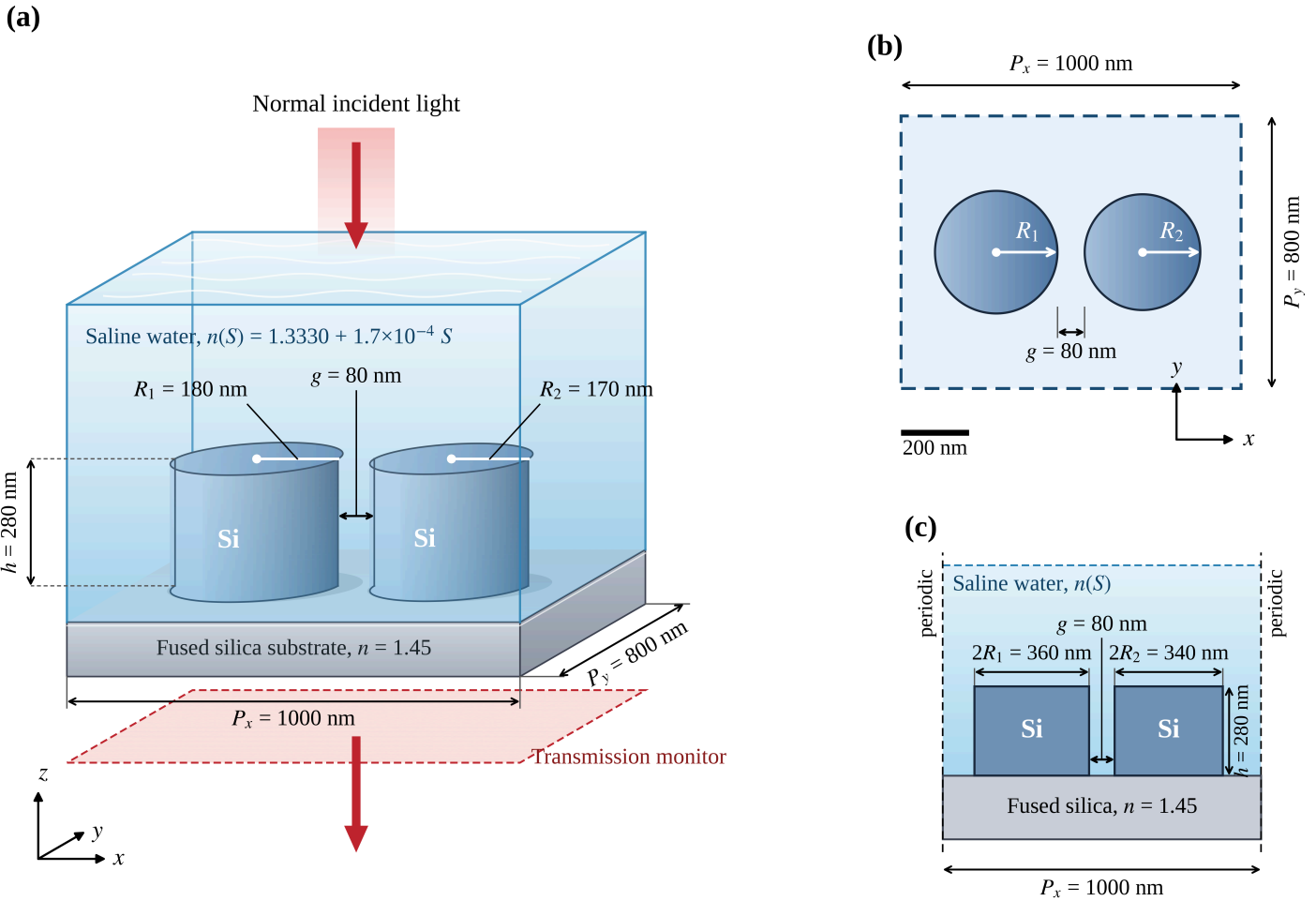


Figure 1

Unit cell of the asymmetric silicon nanodisk dimer metasurface. (a) Oblique view with normally incident light from the saline water side and a transmission monitor below the fused silica; lateral dimensions are to scale, substrate and water thicknesses are not. (b) Top view of one period with the origin at the center of the gap. (c) Cross section at $y = 0$ with the periodic boundaries and layer indices. Parameter values are in Table 1 and the analyte index follows Eq. (1).

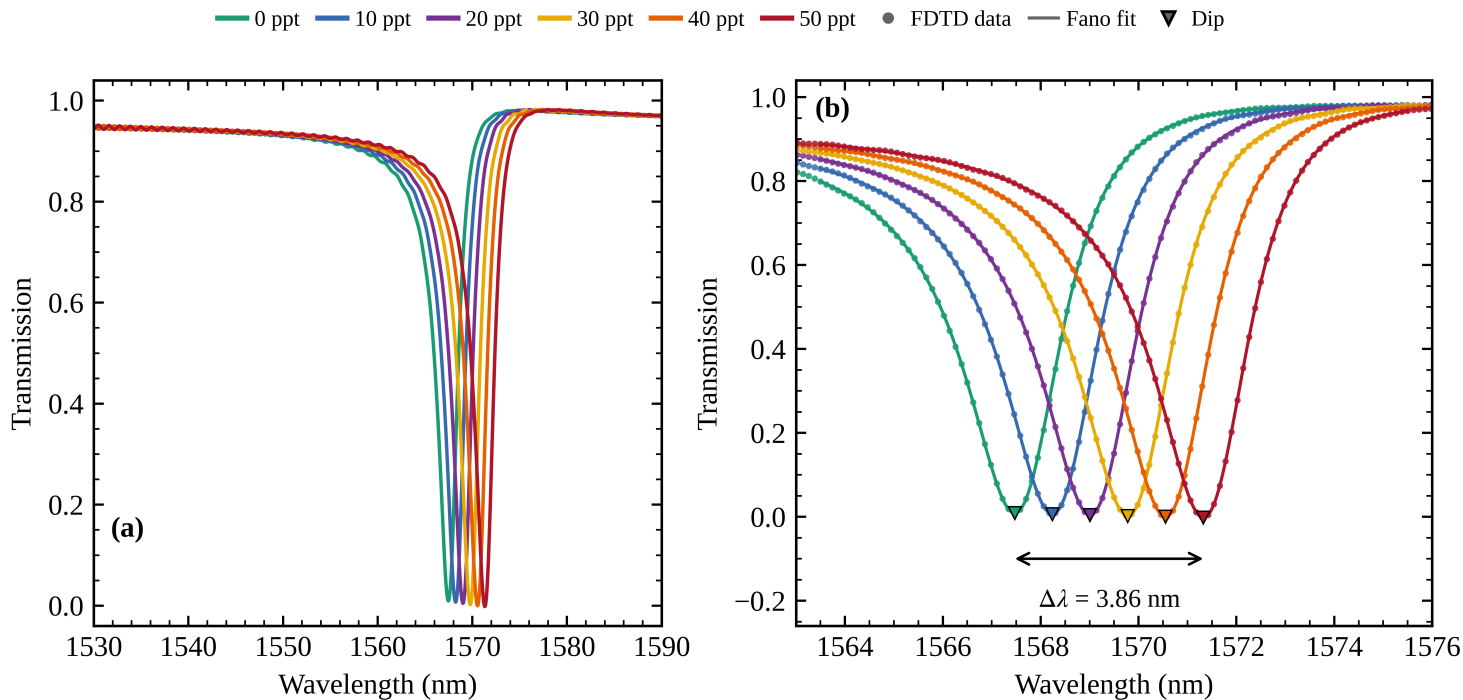


Figure 2

Simulated transmission for six salinities. (a) Full 1530 to 1590 nm window. (b) Enlarged dip: points are FDTD data (every sixth sample), lines are Fano fits, and triangles mark the fitted dip wavelength. The arrow shows the total shift between 0 and 50 ppt

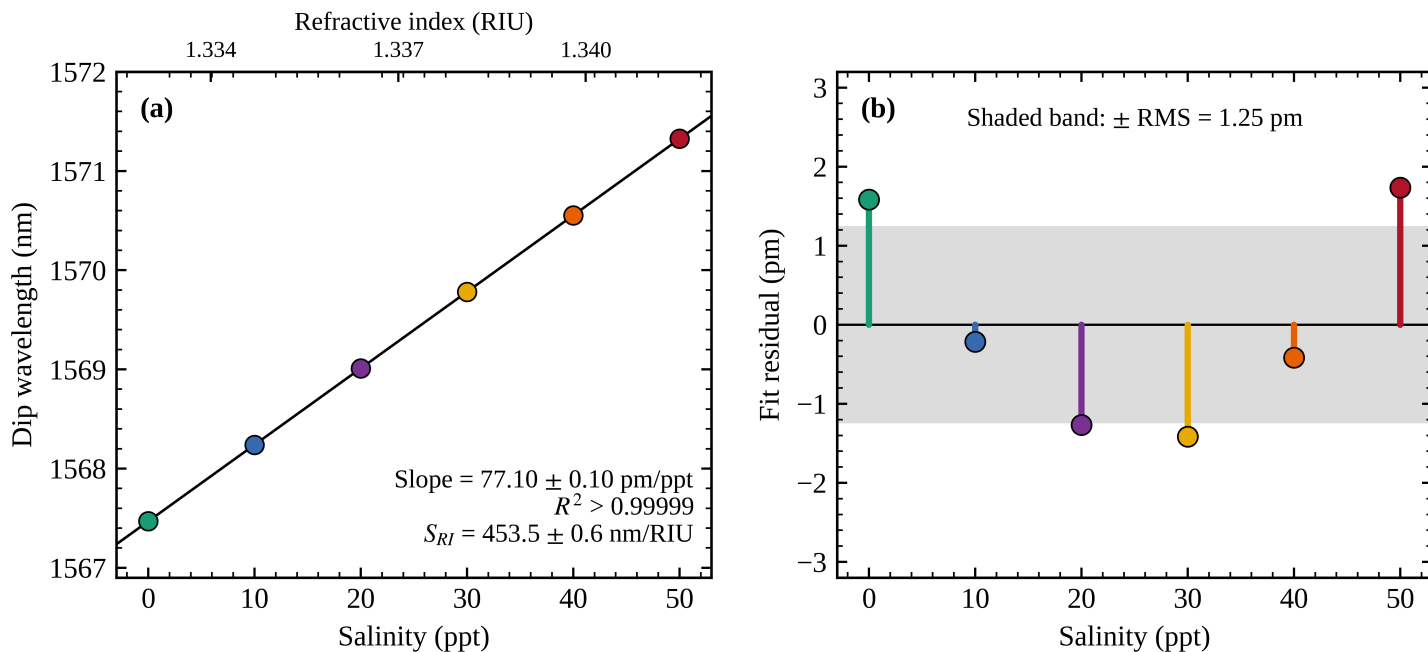


Figure 3

Calibration. (a) Dip wavelength against salinity with the least squares line; the upper axis shows the refractive index from Eq. (1). (b) Fit residuals in picometres; the shaded band is plus and minus the RMS residual.

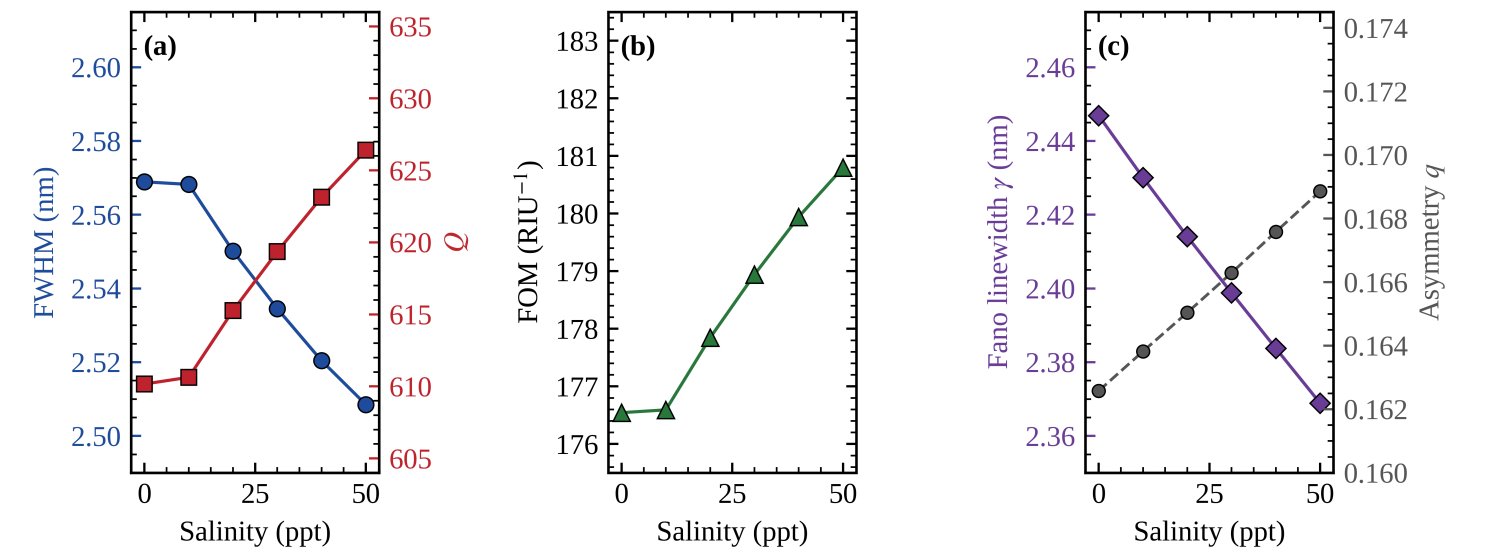


Figure 4

Linewidth metrics. (a) Half depth width (left axis) and Q (right axis). (b) Refractive index figure of merit. (c) Fano linewidth γ (left axis) and asymmetry parameter q (right axis).

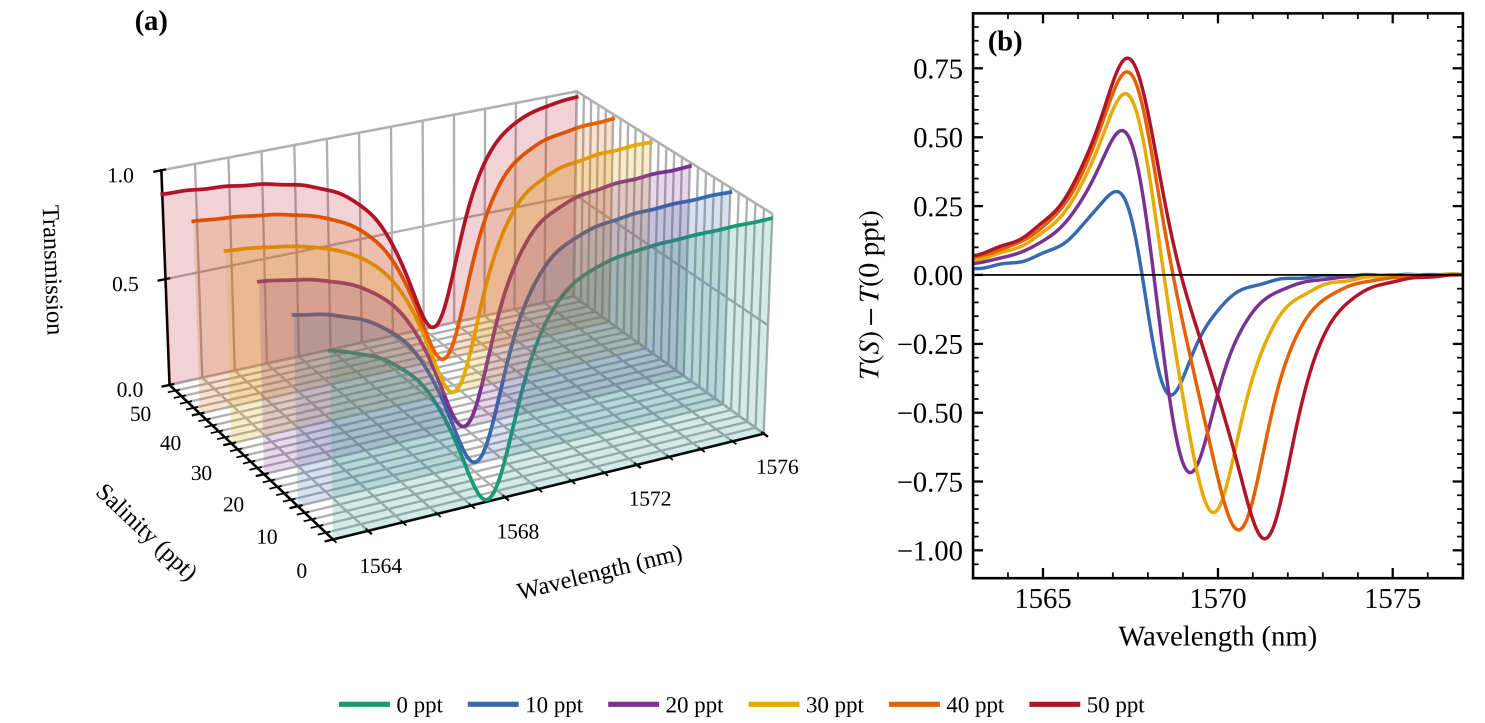


Figure 5

Salinity dependence of the transmission. (a) The six simulated spectra placed at their salinities, with shading down to zero. (b) Spectrum minus the 0 ppt spectrum.

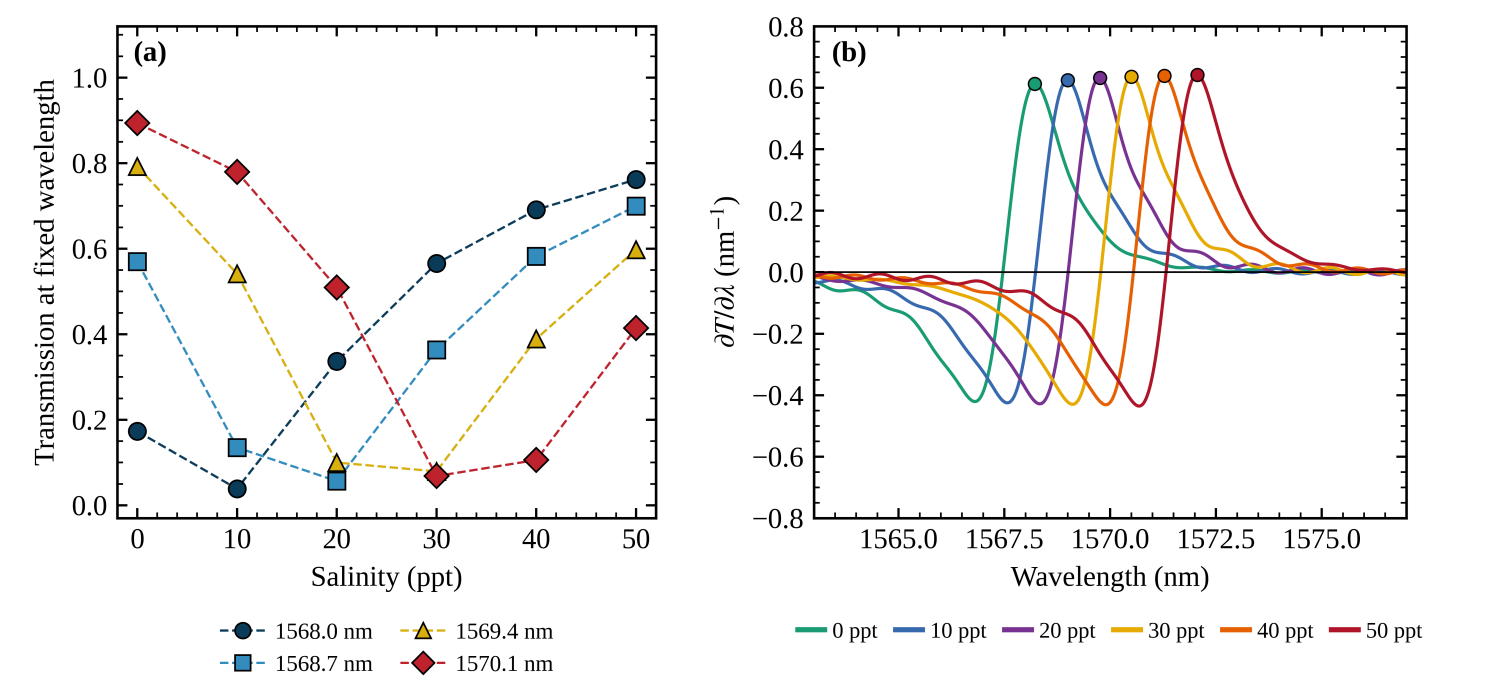


Figure 6

Intensity readout from the simulated spectra. (a) Transmission at four fixed wavelengths for the six salinities; dashed lines connect the sampled points only. (b) Slope of each spectrum; circles mark the steepest point.

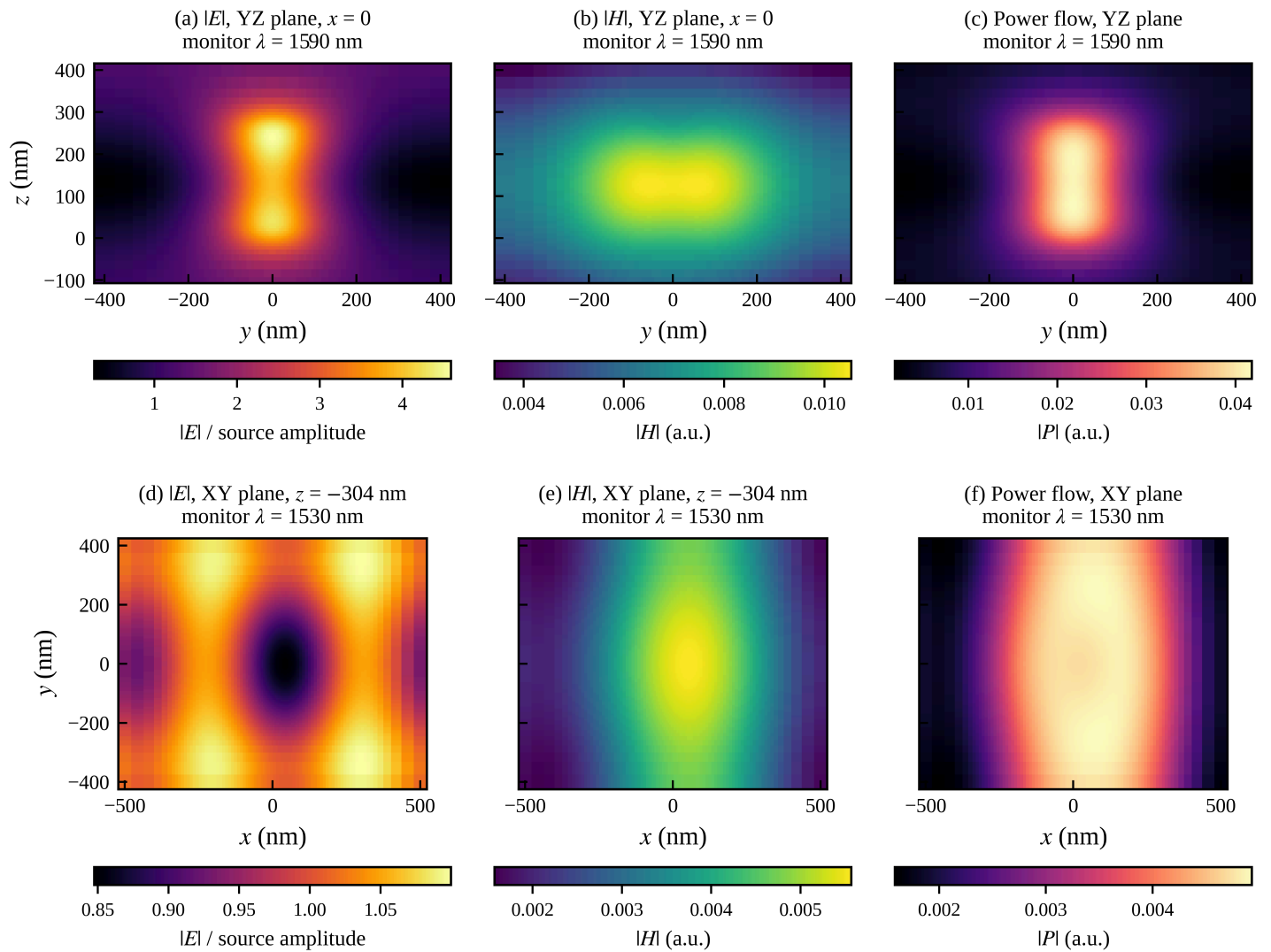


Figure 7

Near field at 0 ppt. Top row: YZ plane at $x = 0$, monitor wavelength 1590 nm. Bottom row: XY plane at $z = -304$ nm, monitor wavelength 1530 nm. Left to right: $|E|$ relative to the source amplitude, $|H|$, and Poynting vector magnitude. Pixels are the monitor samples without smoothing. Structure outlines are omitted because the coordinate origin is not recorded in the exports.

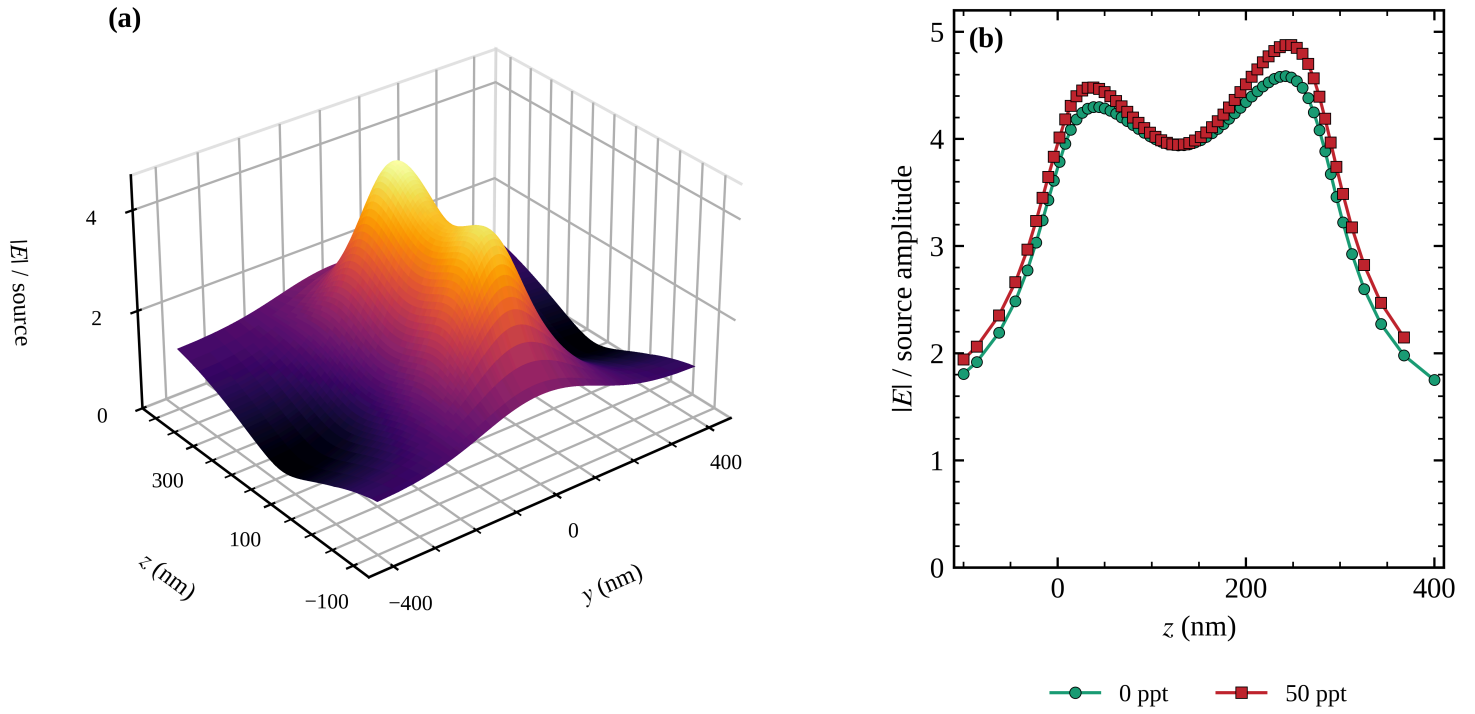


Figure 8

(a) Surface plot of $|E|$ in the YZ plane at 0 ppt (monitor wavelength 1590 nm), from the same data as Fig. 7a. (b) $|E|$ along $y = 0$ for 0 and 50 ppt at the same monitor wavelength; symbols are monitor samples. The 50 ppt monitor is sampled on a slightly different grid and extends beyond the 0 ppt range, so only $z \leq 400$ nm is shown.