Nanoscale shaping and focusing of visible light in planar metal-oxide-silicon waveguides: supplementary materials

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1. OPTICAL SETUP FOR NEAR-FIELD PHASE-RESOLVED IMAGING

We used a transmission mode scattering (apertureless) Scanning Near-field Optical Microscope (s-SNOM, Neaspec Ltd.) to directly measure the near-field signal. The measurement setup is illustrated in Fig. S1. A 671nm continuous wave (CW) semiconductor laser with a circularly polarized beam illuminates the sample from the metal side (from below). The sample was placed on a moving stage, whereas a metallic (Pt\Ir) AFM tip scatters predominantly the out-of-plane electric field component from the Silicon side (from above) into a detector. The tip vibrates at amplitude of approximately 40nm and frequency of about $\Omega = 250\text{kHz}$. In order to maintain an approximately uniform spatial phase and amplitude of the illumination over the scanning area the illumination beam was weakly focused to a 30 μm spot. The incoming laser beam was split into two optical paths for an interferometric pseudo-heterodyne detection; a beam modulated by a vibrating mirror with a frequency of $M = 600\text{Hz}$ was interfered with the signal scattered from the sample to reconstruct the full E-field information including the phase. Therefore, the detected signal is demodulated at higher harmonics $n\Omega + M$ in order to suppress the background signal scattered from the tip[1]. The resolution ability of the s-SNOM is determined by the size of the tip, which is, in our case, between 10-20 nm.

2. SAMPLE FABRICATION

The Silicon planar waveguides were fabricated by deposition of the Silicon-dioxide and silver or gold layers on top of a com-

Fig. S1. Experimental setup for near-field optical imaging
The sample is illuminated from underneath by a weakly focused 671 nm laser beam. The evanescent tail of the coupled guided modes are scattered by an atomic force microscope tip and directed towards a detector where it interferes with a reference beam. The tip oscillates at frequency $\Omega = 250\text{kHz}$ while a piezoelectric driven mirror oscillates the phase of the reference beam at frequency $M = 600\text{Hz}$. Direct far field background is filtered at frequencies $n\Omega + M$ (In the manuscript we present data from $n = 2$ or $n = 3$). The near-field amplitude and phase maps are acquired via scanning the sample.

Fig. S2. Cross-section of the waveguide. (a) Large scale the TEM cross-section of the waveguide from which we measure the thickness of the Silicon membrane- 60nm. (b) High resolution STEM cross-section on a smaller scale shows clearly the triple layer structure Si-SiO₂-Ag. The thickness of the SiO₂ layer is measured to be 4nm.

mercially manufactured free-standing ultrathin poly-crystalline Silicon membrane (Norcada Ltd.), using thin-film sputtering deposition (ATC 2200 by AJA international). Dual-beam focused ion beam (FEI Strata 400s) was used to mill the thin slits into the waveguides from the metal side. In order to accurately determine the layer thicknesses we performed a transmission electron microscopy (TEM) and scanning transmission

electron microscopy STEM measurements using Titan 80-300 FEG-S/TEM (FEI). The TEM measurements were performed on the ($d = 60\text{nm}$, $h = 4\text{nm}$) waveguide, as seen in Fig. S2 whereas the other waveguides' data was determined by extrapolation.

3. THE HYBRID PLASMONIC-PHOTONIC WAVEGUIDE

The Silicon waveguides used in this work support one or two transverse magnetic (TM) short wavelength guided modes. The modes supported by the waveguides have been calculated by solving numerically Maxwell's equations in a layered system. In our calculations, we used the following dielectric functions that match a wavelength of $\lambda = 671\text{nm}$: $\epsilon_{\text{Si}} = 14.58 + 0.11i$ for Silicon [2], $\epsilon_{\text{SiO}_2} = 2.25$ for SiO₂ and $\epsilon_{\text{Ag}} = -20.92 + 0.427i$ for Silver[3]. Table S1 shows the calculated wavelength and propagation length of the supported modes that are presented in the main text.

The profile of the calculated intensity of the electrical field component $|E_z|^2$ (normal to the surface) of the guided modes in the waveguides used in this work is presented in Fig. S3 for single mode waveguide, shown in Fig. S2.2a. and b. for the parameters $d_1 = 60\text{nm}$, $h_1 = 4\text{nm}$ (Si waveguide 1) and $d_2 = 60\text{nm}$, $h_2 = 7\text{nm}$ (Si waveguide 2), respectively, we observe the hybrid photonic-plasmonic[4] characteristics of the mode. These unique modes, hybridizing photonic and plasmonic modes, utilize the strong metallic effect on the plasmon side to better confine the light in the dielectric materials, increasing the effective refractive index of the mode (n_{eff}). Here, a mode guided in a 60nm thick Si waveguide exhibit an effective index that approaches nearly the value of bulk Silicon but with Single-mode operation. For comparison, a bare Si waveguide with similar layer thickness is calculated, showing a much weaker wavelength shortening. The plasmonic effect also decreases the propagation length of the modes, where the Ohmic losses are becoming a more dominant factor for the mode attenuation as the gap layer becomes thinner. Evidently, the thinner SiO₂ gap layer increases the fraction of electric field in the metal, hence shortens the mode wavelength (or increasing the mode index) but also decreases the propagation length. This trade-off between the mode loss and its wavelength shortening can be described by the figure of merit $FOM = 2\pi L_p / \lambda_m$. Additional difference between the two waveguides is the intensity of the evanescent tail in the air, which is important since it determines how efficiently can the guided mode interact with the outer world, e.g., a scatterer. Larger intensity in the air along with lower loss of the guided mode with thicker gap layer result in better Signal-to-Noise ratio (SNR) of the measured near-field maps presented in the main text.

Fig. S3d shows the profile of the dual-mode Si waveguide coated with gold. the layers thicknesses are: $d_3 = 160\text{nm}$, $h_3 = 20\text{nm}$ (Si waveguide 3). The calculated wavelengths of the two supported modes in this waveguide are $\lambda_{m,1} = 200\text{nm}$ and $\lambda_{m,2} = 282\text{nm}$. We observe that the shorter wavelength mode is almost symmetric in the Si part of the waveguide while the longer wavelength mode is anti-symmetric. Interestingly, in the presence of metal the long-wavelength mode, having its node close to the surface, is strongly affected by plasmonic effects, while the symmetric short-wavelength one remains almost unperturbed. Namely, when changing the waveguide's geometry, the shorter-wavelength mode is robust to changes in the outer layer (e.g., the presence or type of metal) and the gap thickness, while the other is highly controllable by changing these parameters.

Si width	SiO ₂ width	Metal	Wavelength (measured)	Wavelength (calculated)	Prop. length (calculated)	F.O.M. (calculated)
60nm±2nm	4nm±0.5nm	Ag	184nm±5nm	184nm	3.3 μ m	113
60nm±2nm	7nm±1.5nm	Ag	213nm±5nm	221nm	4.9 μ m	143
160±5nm	22nm±5nm	Au	200nm±5nm	201nm	5.4 μ m	168
			282nm±5nm	277nm	2.2 μ m	51

Table S1. Summary of the calculated and measure parameters of all samples presented in the main text: Wavelength (measured and calculated), calculated propagation length and calculated figure of merit.

4. THE COUPLING SLITS

The slits coupling the light into the guided modes are designed as two-dimensional lenses that focus the guided modes (propagating in 2D space) to the center of the lens. Fig. S4 shows SEM images of representative slits that were used in the experiments. In this work we use two types of lenses: (1) Archimedean spiral shaped lenses, which when illuminated by circularly polarized light, focus the out-of-plane (normal to the surface) component of the field into a bright spot in the center, and (2) circular lenses that focus similar excitation into a dark spot in the center, as

shown in the main manuscript's Fig. 1 and Fig. 2, respectively.

(1) Archimedean spiral lens. The Archimedean spiral follows the polar (ρ, θ) equation $\rho = \rho_0 + a\theta$, where ρ_0 is the initial radius, and $a\theta$ is the distance between a point in an angle θ and the center of the spiral. Naturally, focusing obtained by this spiral is wavelength dependent. A mode with a wavelength of λ_m sets $a = \lambda_m/2\pi$ such that the out-of-plane component of each antipodal point interfere constructively in the center, similarly to linear polarization demonstrated in [5, 6] but with equal contribution from all angles (points on the spiral), that add up constructively when the polarization is circular [7].

Fig. S3. Longitudinal profiles of the supported modes. Layers thicknesses are: (a) $d_1 = 60\text{nm}$, $h_1 = 4\text{nm}$, (b) $d_2 = 60\text{nm}$, $h_2 = 7\text{nm}$. (c) A bare Si waveguide with $d = 60\text{nm}$ is shown for comparison. Clearly, most of the field resides in air hence the mode's effective index is closer to that of air than that of Si. (d) A waveguide of thicker Si layer $d_3 = 160\text{nm}$, $h_3 = 20\text{nm}$ supports two short-wavelength guided modes. The different materials are distinguished by colors: gray (Ag), blue (SiO₂), green (Si), orange (Au).

Fig. S4. SEM images of the slits used for coupling and focusing the modes (a-b) Archimedean spirals are used for bright spot focusing: (a) A large spiral with an initial radius of $r = 3\mu\text{m}$ was used to focus the single mode of longer wavelength supported in waveguide 2. (b) A smaller spiral was used to focus the shorter wavelength mode in waveguide 1, due to its smaller propagation length. Because of the losses, a grating of spirals has to be used in order to introduce more energy to the signal and to improve the coupling (grating periodicity - 190nm). (c-d) Circles for dark spot focusing. (c) A grating of circles with a periodicity $p = 190\text{nm}$ and a radius of $2\mu\text{m}$ was used to focus the short wavelength mode in waveguide 1 into a vortex. (d) A grating of circles with a periodicity $p = 200\text{nm}$ and a radius $r = 4.51\mu\text{m}$ was used to observe the Super-Oscillations on waveguide 3. In all cases the SEM images were taken from the metal side, where the slits have been milled.

(2) A lens made of circularly shaped slit focuses circularly polarized light in a totally different manner: all antipodal points interfere destructively and focus into a bright doughnut shaped beam with a dark spot in its center. Moreover, since the out-of-plane component carry the opposite phase when propagating towards each other, a spiraling phase pattern is created.

5. SUPER-OSCILLATIONS

The basic principle of Super-Oscillations (SO) is presented in Fig S5. The interference of two standing-wave patterns with different periodicities can result in oscillations (zero-crossings) faster than the fastest frequency, i.e., correspond to non-existing Fourier component. Optimal generation of SO requires equal amplitude of the two waves and its location depends on the relative phase between them.

Direct Observation of super oscillations between two short-wavelength modes requires careful design of the system parameters to achieve precise phase and amplitude relations in a well defined spot. In particular, the requirements for the current observation are as follows: (1) the point of observation was chosen in the focal spot to achieve maximal signal. (2) We choose a dipole-like focus (zero-amplitude in the center) in order to ob-

Fig. S5. Super-Oscillations (a) The basic principle of Super-Oscillations. The interference pattern of two standing waves at different periodicities (marked in green and blue) creates a beating pattern (black) with zero crossings faster than the fastest periodicity. These Super-Oscillations are seen here in the center of the pattern as a result of the relative phase between the two standing waves. (b) Zoom in of the Super-Oscillations in the central part, amplitude (black) and phase (red). (c) cross-section of large-view experimental scan, showing the SO in the center of the beating pattern.

serve a double-peak (3 zero crossings) SO rather than a single peak. (3) the amplitudes of both modes at the focal spot should be similar and (4) the relative phase between them should be π in order to achieve nearly destructive interference. When the two mode wavelengths are known, both amplitude and phase ratios can be tailored by proper design of the coupling slits.

Conditions (1) and (2) are achieved by using a circular slit with linear polarization. For the Super-Oscillating modes presented in the manuscript (Fig. 4) we used a grating of 3 circular slits to enhance the shorter wavelength mode which is inferior to its longer-wavelength counterpart in terms of coupling coefficient and the amplitude of its evanescent tail in air (see Fig. S3c). Moreover, the long-wavelength mode has a larger fraction of the field in the metal, therefore suffers larger dissipation during propagation. This provides an additional mechanism to tune the amplitude ratio by controlling the distance from the excitation point to the focal spot, i.e. the slit radius. The Fourier analysis (manuscript's Fig. 4c) shows indeed that the two modes show comparable signal. Finally, the out-of-phase condition tuning is achieved by setting the radius of the circular slit to $r = (N + 1/2)\lambda_{beat}$, where N is an integer, and λ_{beat} is the beating wavelength of the interference pattern of the two modes $\lambda_{beat} = \lambda_1\lambda_2/(\lambda_1 - \lambda_2)$. A circular slit with a radius of $r = 4.51\mu\text{m}$ equals approximately 6.5 times the beating wavelength $\lambda_{beat} = 688\text{nm}$ hence achieve both conditions (3) and (4).

6. THE GREEN FUNCTION AND POINT-SPREAD FUNCTION

The Greens function to the two-dimensional Helmholtz equation $\nabla^2 E + k^2 E = 0$ for a source located in the 2D plane at position $\vec{r}_0$ is the zeroth order Hankel function of the first kind, $G(\vec{r}, \vec{r}_0) = H_0(k|\vec{r} - \vec{r}_0|)$. This Green's function representing free propagation in 2D is translation invariant, namely it depends only on the relative distance and not on the vectorial location. Therefore in polar coordinates, (ρ, θ) , the Green's function is dependent only on the radial part (ρ). The Green's function of the problem enables to analytically calculate the field distribution of coherent polarized light scattering into guided modes by a subwavelength slit, since the illuminated slit can be modeled as a distribution of point sources in a two dimensional medium.

Fig. S6. Theoretically calculated field distribution of dark and bright spots in 2D homogenous media under circularly polarized illumination. Intensity (a) and phase (b) distribution resulting from an Archimedean spiral distribution of sources. Intensity (c) and phase (d) distribution resulting from a circular distribution of sources.

For example, integrating over dipole sources distributed as Archimedean spiral results in a Bessel function of the zeros order $E(\rho, \theta) = J_0(k\rho)$ for the out-of-plane electric field. Figs. S6a-b show the calculated intensity and phase that results from the spiral source distribution. Not surprisingly, this distribution is also the imaginary part of the Green's function (the non diverging part of the Hankel function). From a microscopy perspective, these images represent the theoretical limit to the Point-Spread-Function (PSF): even for a perfect time-reversed mirror (the slits) only the non-diverging component of the source can be recreated (the imaginary part of the Green's function), while to recreate the singularity it is necessary to time-reverse also the source into a sink.

Changing the source distribution into a circle allows to modify the Point-Spread-Function. The resulting electrical field

is the Bessel function of the first order, with a helical phase $E(\rho, \theta) = CJ_1(k\rho)e^{i\theta}$, as seen in Fig. S6c-d.

Through this work we have not shown imaging capabilities. Nevertheless it is worth mentioning that the translation invariance of the system guarantees that the Point-Spread-Function will be constant during any scanning mechanism for future imaging.

7. DEVICE EFFICIENCY AND FIELD ENHANCEMENT

In order to estimate the performance of our focusing platform we examined the expected focusing efficiency and field enhancement from an optimal structure. We define the efficiency of the lens as the fraction of the incident power into the device that was directed by the lens into the main lobe. In the optimal case, the incident light can be focused using an axicon to a diffraction limited ring with the radius of the lens. In that case, the efficiency of the lens would be given by $\eta_{tot} = \eta_c \cdot \eta_l$, where η_c is the coupling efficiency (or the excitation efficiency) and η_l is the loss effected efficiency. The coupling efficiency to similar modes have been investigated thoroughly in the literature, and we can estimate it would be in the range of 0.2 – 0.45 [8]. The loss-effected efficiency is dependent on the propagation length (l_p) of the modes and the radius of the lens (r), and is given by $\eta_l = \exp(-r/l_p)$. In the case presented here ($r = 3\mu m$) the loss-effected efficiency is $\eta_{l,1} = 0.29$ for the ($60 = 60nm, h = 4nm$) waveguide, and $\eta_{l,2} = 0.16$ for the ($60 = 60nm, h = 4nm$) waveguide. Hence the total efficiency would be in the order of $\eta_{tot,1} = 0.05 - 0.14$ for the $7nm$ gap thickness waveguide and $\eta_{tot,2} = 0.025 - 0.07$ for the $4nm$ gap thickness waveguide. For comparison, a plasmonic lens with a similar radius on a Gold-air interface (where the calculated propagation length of the plasmonic mode is $\lambda_{p,Au} = 21\mu m$) would be about two times better in efficiency compared to the $7nm$ gap waveguide due to the higher propagation length. The other factor that characterizes the focusing device is the field enhancement. We define the field enhancement as the ratio between the optical power per unit area in the main lobe of the focus to that of the incident beam. Figure S7 presents a theoretical comparison between the intensity patterns generated by the MOS platforms and a gold-Air interface with a similar lens radius. The comparison assumes a similar incident energy and does not include the coupling efficiency. From the intensity profiles it is clear that even though the losses of the MOS platform are higher than a gold-air interface, not only does the focus becomes significantly sharper, but the expected field enhancements are in the same order of magnitude, with a small advantage for the MOS platform. The ratio between the calculated field enhancement of the MOS platform and the gold-air interface platform is 1.25 for the $7nm$ gap layer waveguide, and 0.8 for the $4nm$ gap layer waveguide.

REFERENCES

1. N. Ocelic, A. Huber, and R. Hillenbrand, "Pseudo-heterodyne detection for background-free near-field spectroscopy," *Appl Phys Lett* **89**, 101124 (2006).
2. D. E. Aspnes and A. A. Studna, "Dielectric functions and optical parameters of si, ge, gap, gaas, gasb, inp, inas, and insb from 1.5 to 6.0 ev," *Phys. Rev. B* **27**, 985–1009 (1983).
3. P. B. Johnson and R. W. Christy, "Optical constants of the noble metals," *Phys Rev B* **6**, 4370–4379 (1972).
4. R. F. Oulton, V. J. Sorger, D. A. Genov, D. F. P. Pile, and X. Zhang, "A hybrid plasmonic waveguide for subwave-

Fig. S7. Comparison between the lens focusing performance in the MOS platform to Gold-air interface. (a) A line-cut of the intensity pattern in MOS platform with $d_1 = 60nm$, $h_1 = 7nm$ and Ag as the metal (solid blue line) compared to Gold-Air interface (red dashed line) (b) A line-cut of the intensity pattern in MOS platform with $d_1 = 60nm$, $h_1 = 4nm$ and Ag as the metal (solid blue line) compared to Gold-Air interface (red dashed line). All comparisons assume similar coupling.

length confinement and long-range propagation,” *Nat Photon* **2**, 496–500 (2008).

5. Z. Fang, Q. Peng, W. Song, F. Hao, J. Wang, P. Nordlander, and X. Zhu, “Plasmonic focusing in symmetry broken nanocorrals,” *Nano Lett* **11**, 893–897 (2011).
6. B. Gjonaj, A. David, Y. Blau, G. Spektor, M. Orenstein, S. Dolev, and G. Bartal, “Sub-100 nm focusing of short wavelength plasmons in homogeneous 2D space,” *Nano Lett* **14**, 5598–5602 (2014).
7. Y. Gorodetski, A. Niv, V. Kleiner, and E. Hasman, “Observation of the spin-based plasmonic effect in nanoscale structures,” *Phys. Rev. Lett.* **101**, 043903 (2008).
8. I. P. Radko, S. I. Bozhevolnyi, G. Brucoli, L. Martín-Moreno, F. J. García-Vidal, and A. Boltasseva, “Efficiency of local surface plasmon polariton excitation on ridges,” *Phys. Rev. B* **78**, 115115 (2008).