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Author/s:

Sulejman, SB;Wesemann, L;McCormack, M;Meng, J;Hutchison, JA;Priscilla, N;McColl, G;Read, K;Sim, W;Sukhorukov, AA;Crozier, KB;Roberts, A

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Metasurfaces for infrared multi-modal microscopy: phase contrast and bright field - supporting information

Shaban B. Sulejman,^{*,†} Lukas Wesemann,[†] Mikkaela McCormack,[‡] Jiajun Meng,[†] James A. Hutchison,[¶] Niken Priscilla,[†] Gawain McColl,[§] Katrina Read,^{||} Wilson Sim,[⊥] Andrey A. Sukhorukov,[#] Kenneth B. Crozier,^{†,@} and Ann Roberts^{*,†}

[†]*ARC Centre of Excellence for Transformative Meta-Optical Systems, School of Physics,
The University of Melbourne, Victoria 3010, Australia*

[‡]*Dorevitch Pathology, Heidelberg, Victoria 3084, Australia*

[¶]*ARC Centre of Excellence in Exciton Science, School of Chemistry, The University of
Melbourne, Victoria 3010, Australia*

[§]*Florey Institute of Neuroscience and The University of Melbourne, Parkville, VIC 3010,
Australia*

^{||}*St Vincent's Private Hospital, East Melbourne, Victoria 3065, Australia*

[⊥]*School of Science, RMIT University, Melbourne, Victoria 3001, Australia*

[#]*ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS),
Department of Electronic Materials Engineering, Research School of Physics, The
Australian National University, Canberra, ACT 2601, Australia*

[@]*ARC Centre of Excellence for Transformative Meta-Optical Systems, Department of
Electrical and Electronic Engineering, The University of Melbourne, Victoria, 3010,
Australia*

E-mail: sulejmans@unimelb.edu.au; ann.roberts@unimelb.edu.au

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26 S1 Theory

27 S1.1 Image processing

28 The fundamental concepts for the application of the metasurface to tunable multi-modal
 29 microscopy are briefly described in the main article. Here, the explanation is expanded
 30 to explain how the metasurface operates in the formation of images. Consider a source of
 31 monochromatic plane waves with an electric field $\vec{E}_s(x, y, z)$, wavelength λ and wave-vector
 32 \vec{k} propagating along the z -axis. Assuming polarized light and ignoring vector effects for
 33 now for illustration, suppose that this source of light illuminates a semi-transparent sample
 34 located in the $z = 0$ plane with a transmission function $O(x, y) = O_0(x, y)e^{i\varphi(x, y)}$ in the
 35 Kirchhoff approximation. Here, $O_0(x, y)$ represents the amplitude features of the sample
 36 and $\varphi(x, y)$ represents the phase features. This defines an optical image in the $z = 0$ plane
 37 with an intensity profile given by $I_0(x, y) = |O(x, y)|^2 = |O_0(x, y)|^2$, which represents the
 38 bright field image of the sample. Visualizing the transparent features of the sample requires
 39 highlighting the phase shifts imparted onto the light transmitted through the sample, which
 40 can be modelled as,

$$\vec{E}_{\text{in}}(x, y) = O_0(x, y)e^{i\varphi(x, y)}\vec{E}_s(x, y) . \quad (\text{S1})$$

41 The metasurface filters the spatial frequency components of an image in either the object
 42 plane of the sample, the image plane or any plane thereafter that differs only by a free-
 43 space phase shift from the object plane. The optical response of the metasurface in k -space
 44 is characterized by the optical transfer function, which is defined as the Fourier transform
 45 of its Green's function. In general, the optical transfer function is a rank-2 tensor (to

46 accommodate polarization) given in the $\{p, s\}$ -polarization basis as,

$$H(k_x, k_y) = \begin{pmatrix} H_{pp}(k_x, k_y) & H_{ps}(k_x, k_y) \\ H_{sp}(k_x, k_y) & H_{ss}(k_x, k_y) \end{pmatrix}. \quad (\text{S2})$$

47 The spatial frequencies k_x , k_y and $k_z = \sqrt{|\vec{k}|^2 - k_x^2 - k_y^2}$ are the Cartesian projections of \vec{k} ,
 48 where $k_0 = |\vec{k}| = 2\pi/\lambda$ is the wavenumber. As in Ref.,¹ the spatial frequency components
 49 can be represented as a function of the spherical coordinates ($r = k_0, \theta, \phi$),

$$\begin{aligned} k_x &= k_0 \sin(\theta) \cos(\phi) \\ k_y &= k_0 \sin(\theta) \sin(\phi) \\ k_z &= k_0 \cos(\theta) , \end{aligned} \quad (\text{S3})$$

50 where (θ, ϕ) are the polar and azimuthal propagation angles of the plane waves with respect
 51 to the z -axis, respectively. Any light beam can be decomposed into bundles of weighted
 52 plane waves, each travelling in different directions, by the Fourier transform,²

$$\mathcal{F}\{E(x, y)\}(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x, y) e^{-i(k_x x + k_y y)} dx dy , \quad (\text{S4})$$

53 where \mathcal{F} is the Fourier transform operator. Also, given that the optical transfer function
 54 represents the response of the metasurface to plane waves in k -space, then it follows that
 55 the spatial frequency dependence of the metasurface in k -space is equivalent to an angular
 56 dependence in real space. This is the concept that is fundamental to the design of the
 57 metasurface.

58 The impact of the metasurface on an input image is determined by the Green's function
 59 of the metasurface. The output image is given by a convolution integral between the input

60 image and the Green's function,

$$E_i(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G_{ij}(x - x', y - y') E_j^{\text{in}}(x', y') dx' dy' , \quad (\text{S5})$$

61 where $G(x, y)$ is the Green's function tensor and E_i is the i^{th} -component of the output electric
62 field. However, by the convolution theorem, the impact of the metasurface on the spatial
63 frequency spectrum of the input image can be directly modelled as,

$$\tilde{E}_i(k_x, k_y) = H_{ij}(k_x, k_y) \tilde{E}_j^{\text{in}}(k_x, k_y) , \quad (\text{S6})$$

64 where $\tilde{E} = \mathcal{F}\{E\}$. The convolution theorem simplifies the relationship between the input
65 image and the output image from a convolution in real space to a multiplication with the
66 optical transfer function in k -space. The output electric field E can be recovered from \tilde{E} by
67 the inverse Fourier transform,

$$\mathcal{F}^{-1}\{\tilde{E}(k_x, k_y)\}(x, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{E}(k_x, k_y) e^{i(k_x x + k_y y)} dk_x dk_y , \quad (\text{S7})$$

68 where \mathcal{F}^{-1} is the inverse Fourier transform operator and $E = \mathcal{F}^{-1}\{\tilde{E}\}$. Therefore, given
69 the following property for the Fourier transform of a derivative,

$$\mathcal{F} \left\{ \frac{\partial E}{\partial x} \right\} (k_x, k_y) = i k_x \tilde{E}(k_x, k_y) , \quad (\text{S8})$$

70 then a linear optical transfer function, $H \propto k_x$, can produce the spatial derivative (up to
71 a multiplicative constant) of an incoming light field along the x -direction. It follows that a
72 metasurface with an approximately linear angular dispersive transmission $T(\theta) \propto \sin(\theta) \approx \theta$
73 (for $\phi = 0$ and small values of θ) is capable of phase contrast imaging. Here, the $\{p,$
74 $s\}$ -polarization basis was used but, in general, the optical transfer function tensor can be
75 expressed in any polarization basis. Henceforth, we utilize an $\{x, y\}$ basis, i.e. $H_{xx}, H_{xy},$

76 H_{yx} and H_{yy} , describing the impact of the metasurface on the transverse components of the
77 incident field. It was shown in the main article that if we let the x -axis be aligned with
78 the long axis of the silicon blocks for an un-tilted metasurface (normal incidence), then the
79 metasurface has an approximately linear optical transfer function at a tilt of 2° about the
80 y - (short) axis for x -polarized illumination, i.e. $H_{xx} \propto k_x + k_{x0}$, where k_{x0} is a constant.
81 This can compute the derivative along the x -direction, plus a constant offset that pertains
82 to a non-zero background in the output image. Hence, the design of the metasurface was
83 carried out by optimizing the angular response of the metasurface in real space to engineer
84 its optical transfer function in k -space.

85 In the case of a pure phase sample that has $|O_0(x, y)| = \text{constant}$, then the sample is
86 visualized because the phase derivative is converted into intensity variations in the output
87 image $I(x, y)$,

$$I(x, y) \approx \left| O_0 \left(\frac{\partial \varphi(x, y)}{\partial x} + k_{x0} \right) \right|^2. \quad (\text{S9})$$

88 This result is obtained when a linear optical transfer function ($H_{xx} \propto k_x + k_{x0}$) and Eq. (S1)
89 are substituted into Eq. (S6). Hence, the output image is proportional to $|\partial \varphi(x, y)/\partial x|^2$,
90 with contrast created in regions where the phase is varying along the direction of differ-
91 entiation. The constant offset in the optical transfer function is due to the metasurface
92 being slightly tilted by 2° , corresponding to a normalized spatial frequency of $k_{x0}/k_0 \approx 0.03$,
93 that shifts the k -space origin about the angular offset. The increased transmission level at
94 this offset preserves some of the illumination to create a non-zero background in the output
95 image. This distinguishes the imaging modality from dark field imaging that has a dark
96 background in the output image. One could also uniquely distinguish the phase derivatives
97 as they will manifest as different grayscale levels that are above or below the background,
98 corresponding to the region of zero phase gradient, i.e. $I(x, y) \approx |O_0 k_{x0}|^2$.

99 On the other hand, the metasurface was approximately transparent when the illumination
100 was y -polarized. This corresponds to a flat optical transfer function, $H_{yy} \approx \text{constant}$, that
101 only attenuates the input image. In the case that the constant is equal to one, the output

102 image will be exactly the input image. As a result, the output image is proportional to
 103 the bright field image, i.e. $I(x, y) \propto |O(x, y)|^2$. The cross-polarized components of the
 104 optical transfer function H_{xy} and H_{yx} (Fig. S7 and Table S1) are zero in the region of
 105 operation. However, they have some non-zero contributions for larger values of k_x and
 106 k_y , but these contributions were measured to be negligible in the experiments by using an
 107 analyzing polarizer on the output image.

108 The performance of the polarization switching was quantified by the switching contrast
 109 of the metasurface, defined as $\delta = H_{yy}(0, 0) - H_{xx}(0, 0)$. A similar value can be defined
 110 for the switching contrast of the transmittance, given by $\Delta = T_y - T_x$, where T_x and T_y
 111 are the transmittance levels under x - and y -polarized illumination at the operating wave-
 112 length, respectively. The efficiency of the metasurface for image processing is defined as
 113 $\eta = |H_{xx}(k_x^{\max}, 0)|$, where k_x^{\max} is the maximum spatial frequency component where the opti-
 114 cal transfer function of the metasurface is still within its numerical aperture. The numerical
 115 aperture of the metasurface, NA, is defined to be the width of the optical transfer function
 116 where the above conditions are met. This is contrasted from the numerical aperture of the
 117 imaging system itself, which is determined by the optical components in the system.

118 **S1.2 Multipole decomposition**

119 Fig. 2a-iii of the main article shows a multipole decomposition of the transmittance spectrum
 120 of the metasurface. The method from Ref.³ was used to do this and it is briefly summarized
 121 here. Consider a metasurface composed of an array of identical dielectric resonators. For nor-
 122 mally incident, x -polarized illumination, the multipole decomposition of the transmittance
 123 of the metasurface up to second order is given by,

$$T = \left| 1 + \frac{ik}{2E_0 A_{\text{cell}} \epsilon_0 \epsilon_s} \left(p_x + \frac{1}{v_s} m_y - \frac{ik}{6} Q_{xz} - \frac{ik}{2v_s} M_{yz} + \dots \right) \right|^2. \quad (\text{S10})$$

124 Here, $k = 2\pi/\lambda$ is the wave-number in the surrounding, E_0 is the magnitude of the incident
125 electric field, λ is the wavelength of the illumination, A_{cell} is the area of the lattice unit cell, ϵ_s
126 is the relative permittivity of the surrounding and v_s is the speed of light in the surrounding.
127 Furthermore, \vec{p} is the electric dipole moment vector, \vec{m} is the magnetic dipole moment vector,
128 Q is the electric quadrupole moment tensor and M is the magnetic quadrupole moment
129 tensor. The relevant components of the multipole moments are given by,

$$\begin{aligned}
p_x &= \int P_x j_0(kr) dV + \frac{k^2}{10} \int \frac{15j_2(kr)}{(kr)^2} \left((\vec{r} \cdot \vec{P})x - \frac{1}{3}r^2 P_x \right) dV \\
m_y &= -\frac{i\omega}{2} \int \frac{3j_1(kr)}{kr} \left(\vec{r} \times \vec{P} \right)_y dV \\
Q_{xz} &= \int \frac{9j_1(kr)}{kr} (xP_z + P_x z) dV + 6k^2 \int \frac{j_3(kr)}{(kr)^3} \left(5xz(\vec{r} \cdot \vec{P}) - (xP_z + P_x z)r^2 \right) dV \\
M_{yz} &= \frac{\omega}{3i} \int \frac{15j_2(kr)}{(kr)^2} \left((\vec{r} \times \vec{P})_y z + y(\vec{r} \times \vec{P})_z \right) dV,
\end{aligned} \tag{S11}$$

130 where $\vec{r} = (x, y, z)$ is the position vector, j_n is the n^{th} -order spherical Bessel function of the
131 first kind, $\vec{P}(\vec{r}) = \epsilon_0(\epsilon_s - 1)\vec{E}(\vec{r})$ is the polarization density and $\omega = 2\pi f$ is the angular
132 frequency. The integrals are performed over the volume V of the resonator within a single
133 unit cell of the metasurface. This formalism was set up in COMSOL Multiphysics 6.1 to
134 obtain the multipole decomposition of the transmission spectrum of the metasurface.

135 **S1.3 Mie scattering of an isolated resonator**

136 In 1908, Gustav Mie⁴ exactly solved Maxwell's equations for the scattering of plane waves
137 from a homogeneous sphere of size comparable to a wavelength. Although the analytic
138 solution exists only for ellipsoidal particles, the physics is identical for arbitrary geometries.⁵
139 Consider the Mie scattering of plane waves by a rectangular resonator. To characterize its
140 multipolar behaviour, the electric field scattered by the resonator when under plane wave

141 illumination is expanded in the basis of vector spherical harmonics,

$$\vec{E}_{sc}(r, \theta, \phi) = \sum_{n=1}^{\infty} \sum_{m=-n}^{+n} c_{nm} \left(a_{nm} \vec{N}_{nm}(r, \theta, \phi) + b_{nm} \vec{M}_{nm}(r, \theta, \phi) \right), \quad (\text{S12})$$

142 where a_{nm} and b_{nm} are the electric and magnetic scattering coefficients, respectively. The
143 normalization constants are defined as,

$$c_{nm} = |\vec{E}_0| i^{n+2m-1} \sqrt{\frac{(2n+1)(n-m)!}{4(n+m)!}}, \quad (\text{S13})$$

144 where \vec{E}_0 is the electric field of the illumination. Following the formalism from Ref.,⁶ the
145 electric and magnetic harmonics are respectively defined in spherical coordinates as,

$$\begin{aligned} \vec{N}_{nm} &= \frac{1}{k_0 r} \left(\tau_{nm}(\cos(\theta)) \hat{\theta} + i\pi_{nm}(\cos(\theta)) \hat{\phi} \right) e^{im\phi} \frac{\partial}{\partial r} \left(r h_n^{(1)}(k_0 r) \right) \\ &\quad + \frac{n(n+1)}{k_0 r} P_n^m(\cos(\theta)) h_n^{(1)}(k_0 r) e^{im\phi} \hat{r} \\ \vec{M}_{nm} &= h_n^{(1)}(k_0 r) e^{im\phi} \left(i\pi_{nm}(\cos(\theta)) \hat{\theta} - \tau_{nm}(\cos(\theta)) \hat{\phi} \right), \end{aligned} \quad (\text{S14})$$

146 where $h_n^{(1)}$ is the n^{th} -order spherical Hankel function of the first-kind and P_n^m is the n^{th} -order
147 associated Legendre polynomial of degree m . The τ and π functions are defined as,

$$\begin{aligned} \tau_{nm}(\theta) &= \frac{\partial}{\partial \theta} P_n^m(\cos(\theta)) \\ \pi_{nm}(\theta) &= m P_n^m(\cos(\theta)) \csc(\theta). \end{aligned} \quad (\text{S15})$$

148 The scattering coefficients can be computed by projecting the scattered electric field onto
149 the vector spherical harmonics on a virtual sphere of radius r_0 surrounding the resonator,
150 given by,

$$\begin{aligned} a_{nm} &= \frac{\int_0^{2\pi} \int_0^\pi \vec{E}_{sc}(r=r_0, \theta, \phi) \cdot \vec{N}_{nm}^*(r=r_0, \theta, \phi) \sin(\theta) d\theta d\phi}{c_{nm} \int_0^{2\pi} \int_0^\pi |\vec{N}_{nm}(r=r_0, \theta, \phi)|^2 \sin(\theta) d\theta d\phi} \\ b_{nm} &= \frac{\int_0^{2\pi} \int_0^\pi \vec{E}_{sc}(r=r_0, \theta, \phi) \cdot \vec{M}_{nm}^*(r=r_0, \theta, \phi) \sin(\theta) d\theta d\phi}{c_{nm} \int_0^{2\pi} \int_0^\pi |\vec{M}_{nm}(r=r_0, \theta, \phi)|^2 \sin(\theta) d\theta d\phi}. \end{aligned} \quad (\text{S16})$$

151 By using the asymptotic relation $h_n^{(1)}(k_0 r) \sim (-i)^n e^{ik_0 r} / ik_0 r$ for $k_0 r \gg 1$ and the orthonor-
 152 mality of the associated Legendre polynomials, it follows that the scattering cross section is
 153 given by

$$\sigma_s = \frac{\pi}{k_0^2} \sum_{n=1}^{\infty} \sum_{m=-n}^{+n} n(n+1) (|a_{nm}|^2 + |b_{nm}|^2) . \quad (\text{S17})$$

154 The integer $n \in [1, \infty)$ provides the degree of the multipole, i.e. $n = 1$ corresponds to
 155 dipole, $n = 2$ to quadrupole, etc., while the integer $m \in [-n, n]$ provides their orientations
 156 in space. The contribution to the scattering cross section for each n represents the cross
 157 section for that particular degree of the multipole. Furthermore, for each multipole degree,
 158 the electric component corresponds to the a_{nm} term and the magnetic component to the b_{nm}
 159 term. Hence, the total cross section can be decomposed as,⁷

$$\sigma_s = \sigma_s^{ED} + \sigma_s^{MD} + \sigma_s^{EQ} + \dots , \quad (\text{S18})$$

160 where ED, MD and EQ each stand for electric dipole, magnetic dipole and electric quadrupole,
 161 respectively. The Mie resonances of the resonator manifest as peaks in the cross sections at
 162 the resonant wavelengths. This formalism was set up in COMSOL Multiphysics 6.1 to deter-
 163 mine the multipolar decomposition of the scattering cross section for an isolated resonator
 164 from the metasurface.

165 **S2 Additional simulation data**

166 **S2.1 Optical response**

167 Simulations of the optical response of the metasurface were performed using the steps out-
 168 lined in the Methods section of the main article. The metasurface was designed to have
 169 an angle-dependent transmission for x -polarized illumination at the operating wavelength,
 170 and an angle-independent transmission for y -polarized illumination. The angle-dependent
 171 transmission spectra are given in Fig. S1 as a function of the angle of incidence. The results

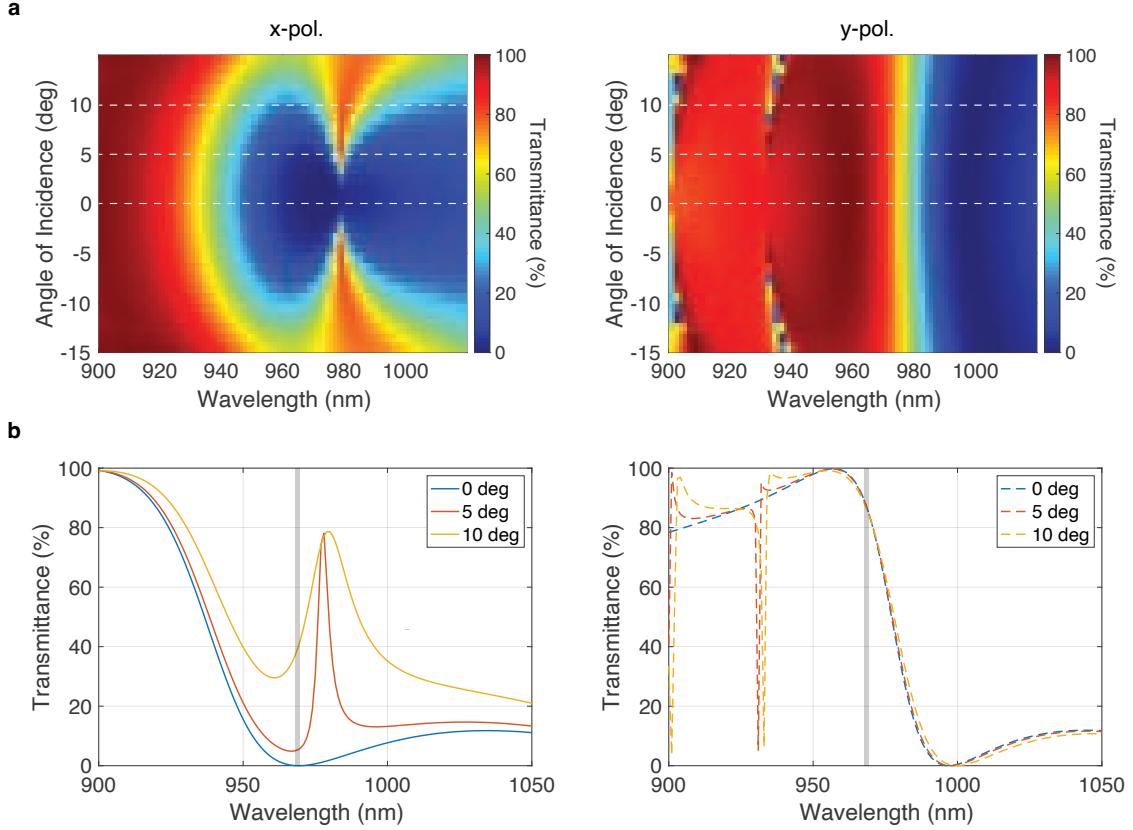


Figure S1: **Angle-dependent transmission spectra.** (a - left) A 2D heat map of the transmission versus the angle of incidence and the wavelength of x -polarized illumination. (a - right) Same as the left but for y -polarization. (b - left) The 1D transmission spectra for 0, 5 and 10 degrees angle of incidence for x -polarized illumination. (b - right) Same as the left but for y -polarized illumination.

172 show that the transmission spectrum changed under x -polarized illumination with a varying
 173 angle of incidence. Meanwhile, the transmission spectrum under y -polarized illumination
 174 remained similar when the angle of incidence was varied, with only the appearance of dark
 175 modes for shorter wavelengths.

176 The 1D plots of the optical response are given in Fig. S2. The reflectance of the meta-
 177 surface is shown to be a maximum at the operating wavelength for x -polarized illumination
 178 and a minimum for y -polarized illumination (Fig. S2a). The absorptance is also shown to
 179 be nearly zero for both cases. The transmission spectra for different states of linear polar-
 180 ization shows how the spectrum morphs between those for x - and y -polarized illumination
 181 (Fig. S2b).

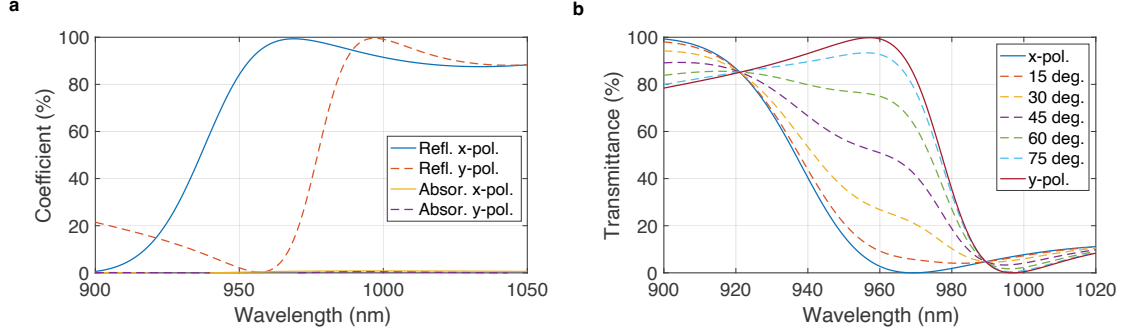


Figure S2: **1D spectra as a function of various parameters.** (a) The reflectance and absorptance spectra of the metasurface for x - and y -polarized illumination. (b) The transmittance spectra as a function of the angle of linear polarization.

182 The operating wavelength of the metasurface is dependent on the geometrical parameters
 183 of the metasurface, including the size of the resonators (length L , width W and height H)
 184 and the lattice constant (P) of the array. The dispersion of the resonance as a function of
 185 the geometrical parameters is shown in Fig. S3. In each case, the resonance red-shifted as
 186 the geometrical parameters were increased.

187 The electromagnetic behavior of the metasurface when on-resonance is depicted in Figs.
 188 S4-S6. They each show the electric field, magnetic field and power flow in the unit cell of the
 189 metasurface at the operating wavelength for x - and y -polarized illumination. The electric
 190 and magnetic fields when on-resonance from x -polarized illumination display behavior that
 191 is linked to an electric dipole resonance, with the power of the fields swirling around the
 192 resonator. On the other hand, the fields behave differently when off-resonance and the
 193 power of the fields flows through the resonator.

194 The magnitude and phase of the optical transfer function are given in Fig. S7. It was
 195 computed as the angle-dependent transmission as a function of the polar and azimuthal
 196 angles of incidence (θ, ϕ). The 1D slices through $k_x = 0$ and $k_y = 0$ are given in Fig. S8.
 197 The results show that the capability of the metasurface to process input images along k_y is
 198 weaker than that for k_x under x -polarization. Moreover, the cross-polarized components of
 199 the optical transfer function are consistent with Ref.⁸ They are non-zero along the diagonals
 200 in Fig. S7(middle column), however the contribution to the output was measured to be small

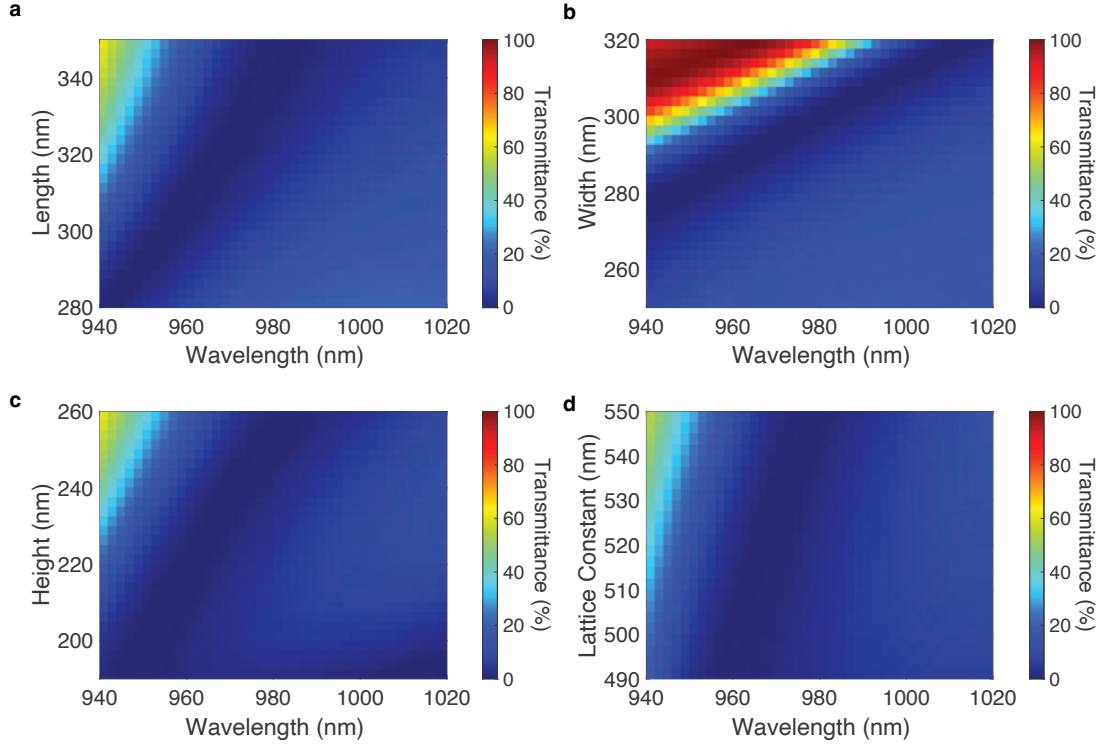


Figure S3: **Dispersion of the resonance.** (a) A 2D heat map of the transmittance spectrum as a function of the length of the resonators. (b) Same as a but for the width of the resonators. (c) Same as a but for the height of the resonators. (d) Same as a but for the lattice constant of the metasurface. In all cases, the illumination was x -polarized.

201 in the experiments.

202 **S2.2 Performance metrics**

203 The performance of the metasurface was quantified through various numerical metrics. These
 204 included the transmittance, reflectance, absorptance, quality factor, electric field enhance-
 205 ment, numerical aperture, angular response, polarization conversion efficiency, processing
 206 efficiency and the switching contrast. The results are tabulated in Table S1 and can be
 207 compared to the experimental results in Table S2. The results show that the metasurface
 208 strongly reflects light when on-resonance with little absorption for normally incident, x -
 209 polarized illumination. The electric dipole resonance had a quality factor of 17.3, which
 210 produced an optical transfer function with a numerical aperture of approximately 0.17.

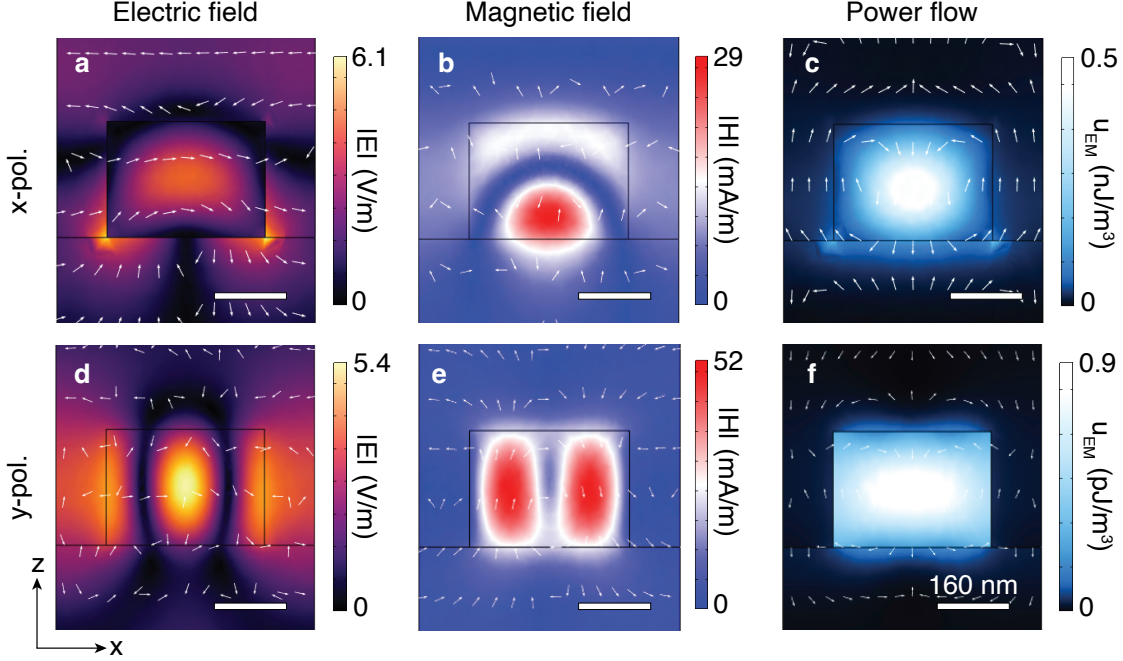


Figure S4: **Electromagnetic behavior of the metasurface in the xz -plane.** (a),(d) The electric field strength (heat map) and direction (arrows) in the unit cell for x - (a) and y -polarization (d). (b),(e) Same as (a),(d) but for the magnetic field. (c),(f) The time-averaged electromagnetic energy density (heat map) and Poynting vector (arrows) in the unit cell for x - (c) and y -polarization (f). All of the images are given in the xz -plane of the metasurface and at the operating wavelength.

211 S2.3 Isolated resonator

212 The optical response of an isolated silicon resonator of size given in the main article was
 213 investigated by implementing the formalism explained in section S1.2. The simulations were
 214 performed using the finite element method within the wave optics module of COMSOL
 215 Multiphysics 6.1. The scattering formulation was used to project the far-zone scattered
 216 electromagnetic field onto the vector spherical harmonics on a virtual sphere of radius $r_0 =$
 217 750 nm surrounding the resonator. Sommerfeld boundary conditions and a perfectly matched
 218 layer were applied onto the virtual sphere to remove unwanted reflections into the system
 219 and to simulate an open domain. The finite meshing elements in the model had a minimum
 220 size of 5 nm and a maximum size of $\lambda/8$ nm. The perfectly matched layer had a series of 5
 221 meshing elements. The scattering cross section was obtained by integrating the projections
 222 of the electromagnetic fields onto the vector spherical harmonics and using Eqs. (S10)-(S15).

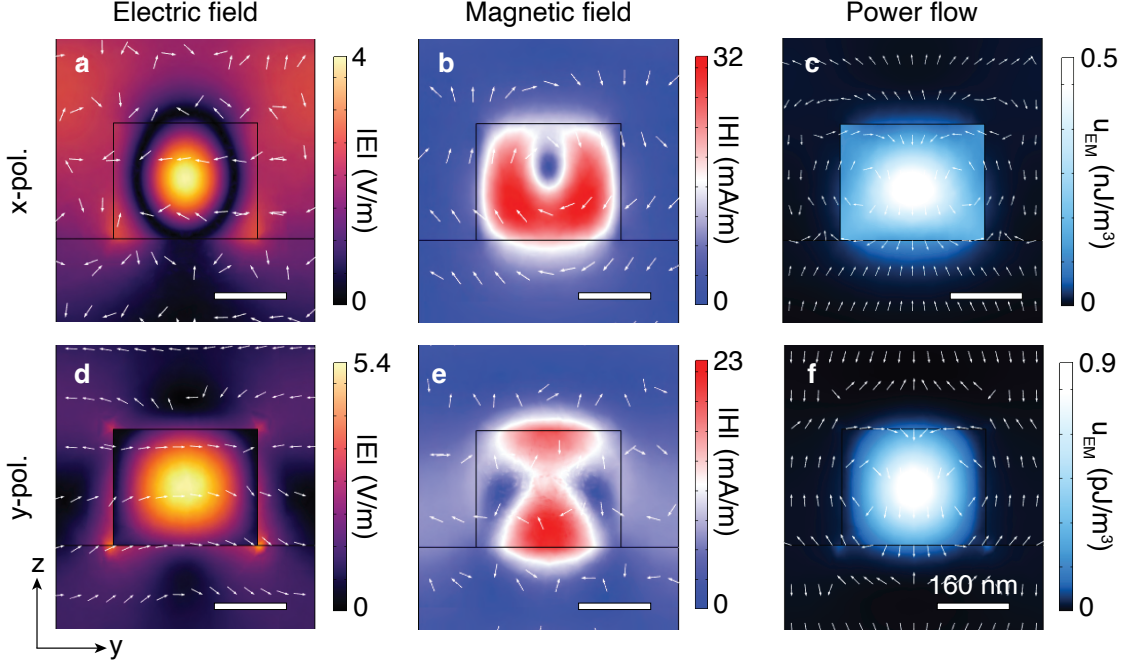


Figure S5: **Electromagnetic behavior of the metasurface in the yz -plane.** (a),(d) The electric field strength (heat map) and direction (arrows) in the unit cell for x - (a) and y -polarization (d). (b),(e) Same as (a),(d) but for the magnetic field. (c),(f) The time-averaged electromagnetic energy density (heat map) and Poynting vector (arrows) in the unit cell for x - (c) and y -polarization (f). All of the images are given in the yz -plane of the metasurface and at the operating wavelength.

223 The results are given in Fig. S9 for the case of normally incident, x -polarized plane
 224 waves illuminating the resonator at the operating wavelength. The 3D (Fig. S9a) and polar
 225 radiation patterns (Fig. S9d) show that majority of the light is concentrated in the forward
 226 direction. The electromagnetic field behavior in the xz -plane shows field enhancement within
 227 the resonator (Fig. S9b-c). The multipole decomposition of the scattering cross section
 228 indicates that this is due to an electric dipole resonance (Fig. S9e).

229 S2.4 Imaging simulations

230 Simulations of tunable multi-modal microscopy were performed in MATLAB R2022a by
 231 the formulations presented in the ‘Tunable multi-modal microscopy - principles’ section of
 232 the main article and in the section S1.1. The optical transfer function of the metasurface
 233 that was calculated in COMSOL Multiphysics 6.1 (Fig. S7) was used to model the optical

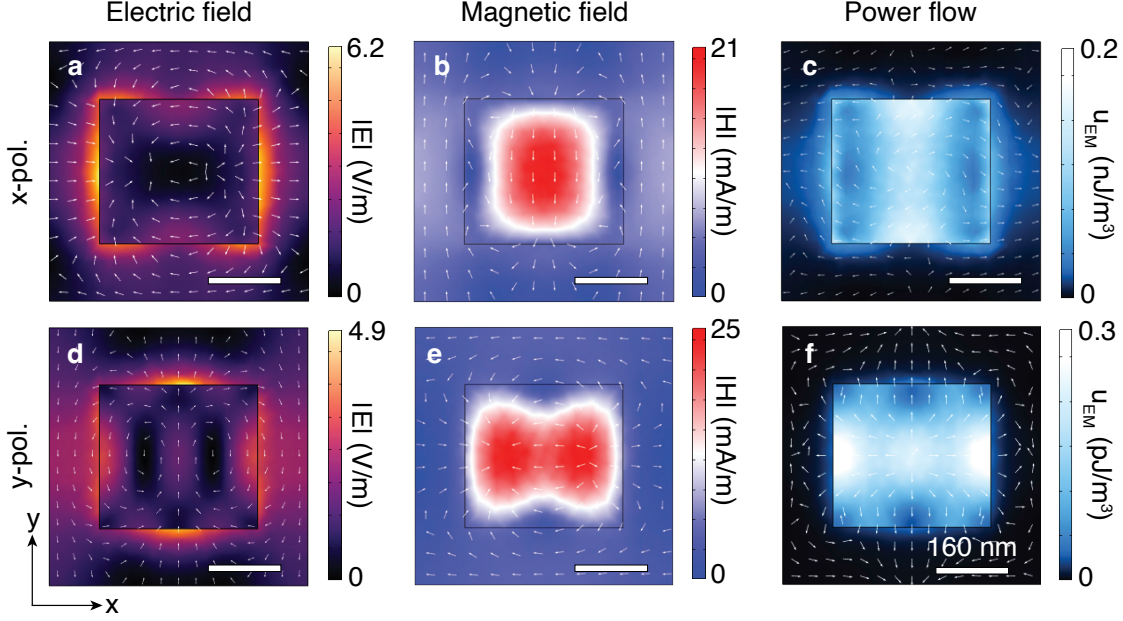


Figure S6: **Electromagnetic behavior of the metasurface in the xy -plane.** (a),(d) The electric field strength (heat map) and direction (arrows) in the unit cell for x - (a) and y -polarization (d). (b),(e) Same as (a),(d) but for the magnetic field. (c),(f) The time-averaged electromagnetic energy density (heat map) and Poynting vector (arrows) in the unit cell for x - (c) and y -polarization (f). All of the images are given in the xy -plane of the metasurface and at the operating wavelength. The slice through the z -plane is taken at the interface between the resonator and substrate.

234 response of the metasurface in Eq. (S6). Three imaging targets were used in the simulations
 235 and experiments. The first included an opaque amplitude mask with the word ‘Amplitude’
 236 and a phase profile of the word ‘Phase’ (Fig. S10 - top left), which was presented in the
 237 main article. The second included the opaque word ‘Erythrocyte’ and the phase profile of a
 238 human red blood cell (Fig. S10 - top middle). Some of the experimental imaging results are
 239 presented in Fig. 1a of the main article. The phase profile of the red blood cell was modelled
 240 using the empirical optical properties provided in Ref.⁹ Lastly, the third imaging target
 241 included the opaque word ‘T-Lymphocyte’ and the phase profile of a leukaemic Jurkat cell
 242 (Fig. S10 - top right).¹⁰ The phase profile of the Jurkat cell was modelled using the empirical
 243 optical properties from Ref.¹¹ and the imaging results for both simulation and experiment
 244 are presented here.

245 The simulated imaging results are presented in Fig. S10. The images obtained with
 246 x -polarized illumination contained both of the transparent and opaque features of the input

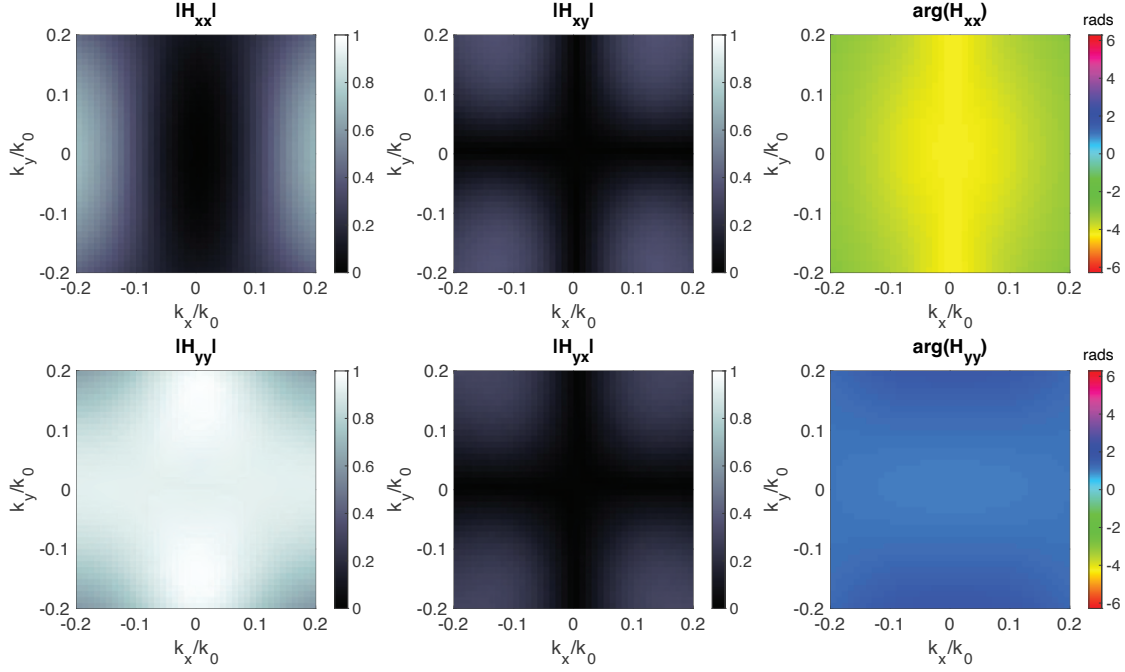


Figure S7: **2D optical transfer function of the metasurface.** The magnitude (first two columns) and phase (last column) of the optical transfer function tensor components at the operating wavelength.

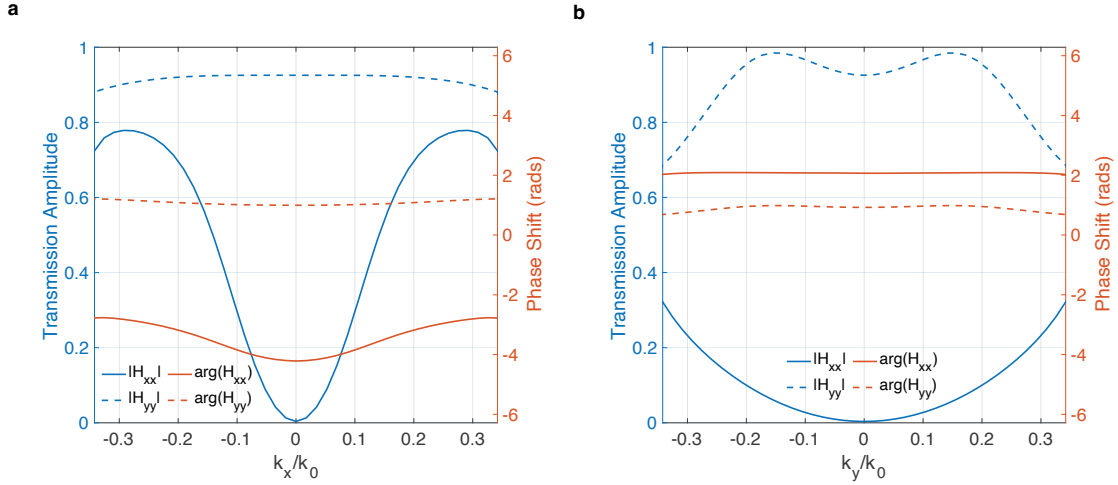


Figure S8: **1D optical transfer function of the metasurface.** (a) The magnitude and phase of the co-polarized components of the optical transfer function along $k_y = 0$. (b) Same as a but along $k_x = 0$.

247 imaging target (Fig. S10 - middle row). Each of the phase profiles have pseudo-3D contrast
 248 visible in the images. On the other hand, only the opaque words are visible in the images
 249 obtained with y -polarized illumination (Fig. S10 - bottom row).

Table S1: **Simulated performance metrics of the metasurface.** The performance metrics were obtained through simulations in COMSOL Multiphysics 6.1 at the operating wavelength of 969 nm, corresponding to the electric dipole resonance of the metasurface. Here, \vec{E}_0 denotes the electric field of the normally-incident, x -polarized illumination. The values k_x^{\max} and k_x^{\min} denote the spatial frequencies at the edges of the contrast zone. E_t and E_r denote the electric field transmitted through, and reflected from, the metasurface, respectively. P_{cross} and P_{in} denote the cross-polarized and input power, respectively. Lastly, $\Delta\lambda$ is the full width at half-maximum of the transmission minimum at the operating wavelength.

Quantity	Label	Formula	Value
Transmittance	T	$ E_t/E_0 ^2$	0.001
Reflectance	R	$ E_r/E_0 ^2$	0.993
Absorptance	A	$1 - T - R$	≤ 0.006
Quality factor	Q	$\lambda/\Delta\lambda$	17.3
Field enhancement	ΔE	$\max(E/E_0)$	6.1
Numerical aperture	NA	$(k_x^{\max} - k_x^{\min})/k_0$	≤ 0.17
Angular response	Θ	$\Delta\lambda/\lambda$	0.06
Polarization conversion efficiency	ϵ_{pol}	$100\%P_{\text{cross}}/P_{\text{in}}$	0.001%
Processing efficiency	η	$ H_{xx}(k_x^{\max}, 0) $	79%
Switching contrast (amplitude)	δ	$H_{yy}(0, 0) - H_{xx}(0, 0)$	93%
Switching contrast (transmittance)	Δ	$T_y - T_x$	86%

250 S3 Optical configurations

251 S3.1 Polarization

252 The metasurface operates under the excitation by linearly polarized illumination. As in the
 253 main article, we define two coordinate systems. The first is the global coordinate system
 254 with respect to the optical bench in the experiment. The second is with respect to the
 255 metasurface defined by the long axis of the silicon blocks, the short axis and the normal to
 256 the metasurface. Assume that the illumination propagates along the global z -axis (optical
 257 axis). The metasurface was placed in the global xy -plane with its long axis aligned with
 258 the global x -axis. It was then tilted by 2° about the global y - (short) axis. Therefore, with
 259 this configuration, x -polarized illumination leads to the production of phase contrast images,
 260 while y -polarized illumination leads to bright field images. A schematic of the polarization
 261 is given in Fig. S11.

262 In the imaging experiments, the global x -axis was along the vertical direction and the

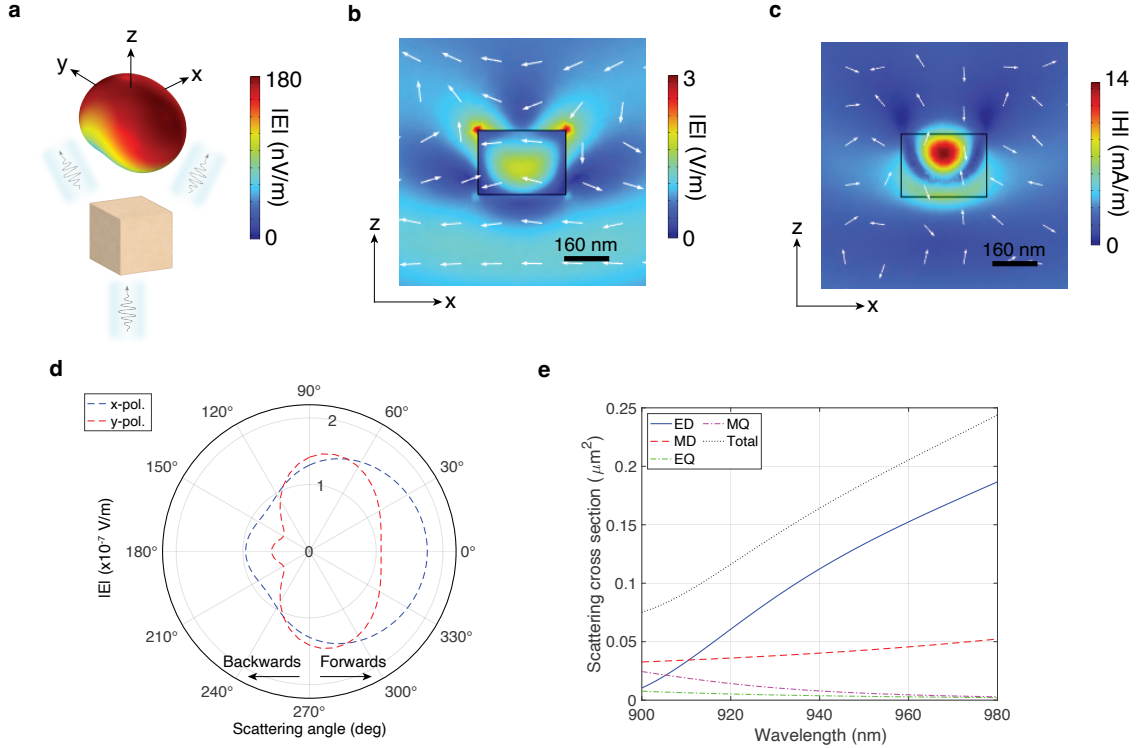


Figure S9: **Optical response of an isolated silicon resonator in air.** (a) The 3D radiation pattern. (b) The electric field strength (heat map) and direction (arrows) when on-resonance in the xz -plane. (c) Same as b but for the magnetic field. (d) The polar radiation plot in the xz -plane for x - and y -polarization. (e) A multipole decomposition of the scattering cross section as a function of the wavelength. The results in (a)-(c) and (e) were obtained with x -polarized illumination at the operating wavelength.

263 global y -axis was along the horizontal direction. The metasurface was oriented with its long
 264 axis along the vertical direction (at normal incidence), as depicted in Fig. S11. To change
 265 the polar angle of incidence θ , the metasurface was tilted about the horizontal direction. The
 266 illumination was x -polarized when the input polarizer was along the vertical direction. On
 267 the other hand, the illumination was y -polarized when the input polarizer was horizontal.
 268 The effects of de-polarization and/or cross-polarization by the spatial light modulator (SLM),
 269 imaging samples, metasurface and optical components were measured to be negligible. For
 270 example, the slight deviations on the polarization set by the polarizer due to diffraction from
 271 the SLM was a weak effect.

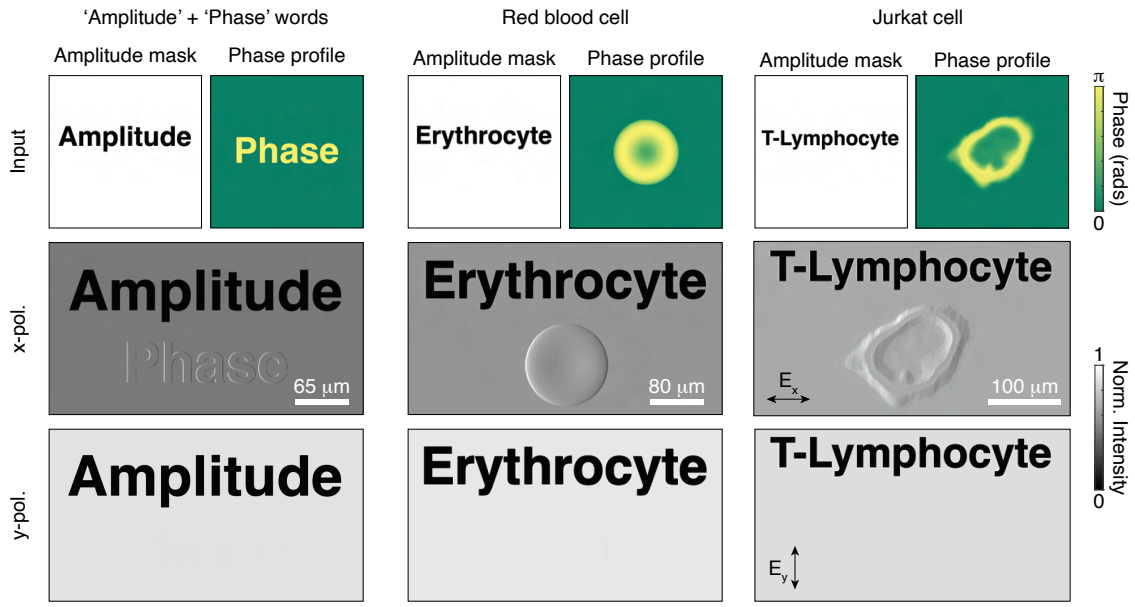


Figure S10: **Simulated tunable multi-modal microscopy with the metasurface.** (First row) The amplitude and phase masks of the input imaging target. (Second row) The output images obtained with x -polarized illumination. (Final row) The output images obtained with y -polarized illumination.

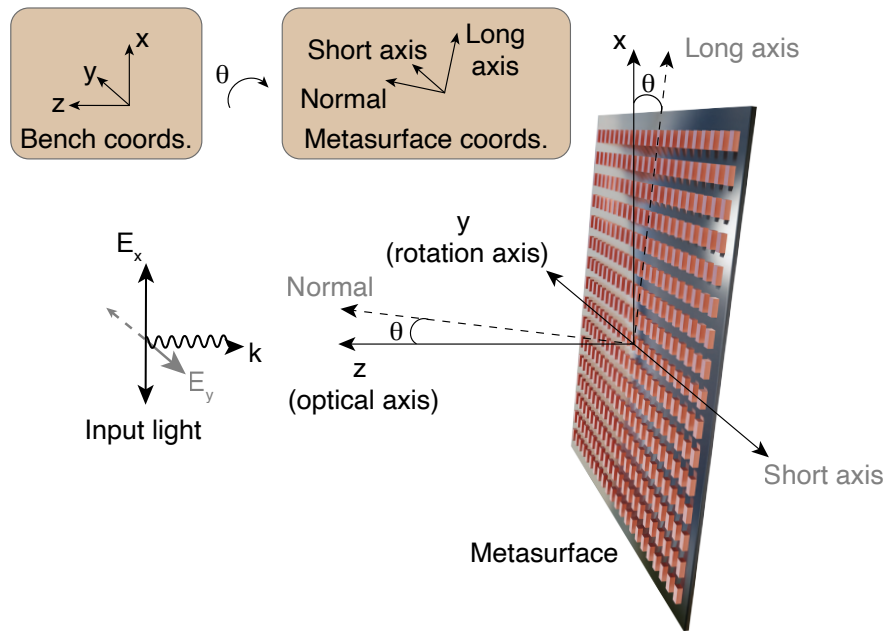


Figure S11: **Polarization.** Schematic of how the polarization is defined and referred to in this article.

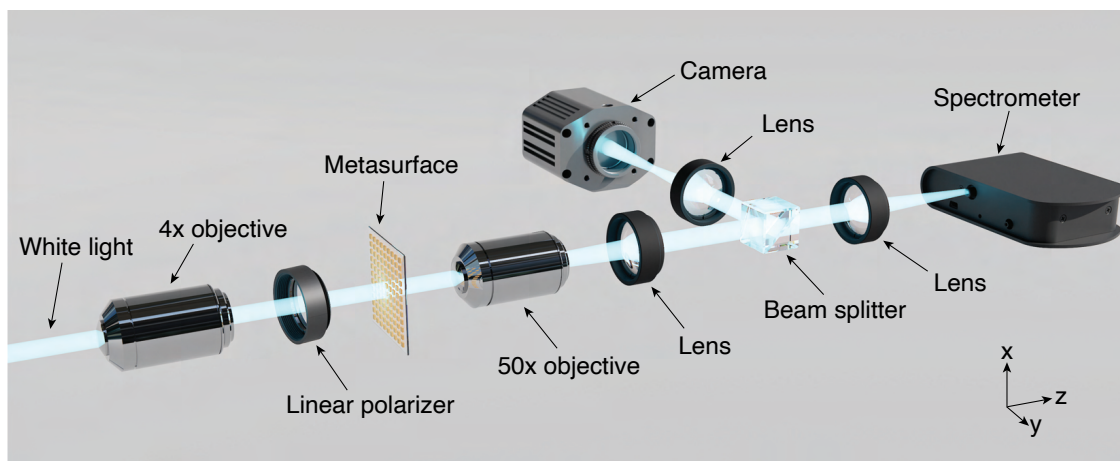


Figure S12: **Normal-incidence spectroscopy configuration.** White light from a halogen lamp was collimated by a microscope objective and linearly polarized. The light transmitted by the metasurface was collected by a second microscope objective and a lens. A second lens focused the transmitted light onto a spectrometer. A beam-splitter was used to simultaneously relay an image of the metasurface onto a camera by a lens.

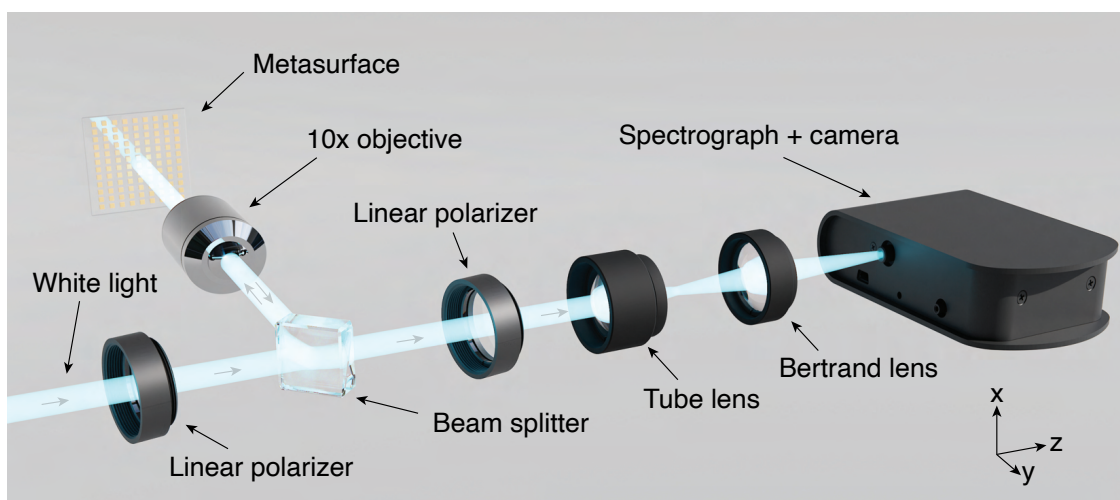


Figure S13: **Angle-dependent spectroscopy via back focal plane imaging.** White light from a halogen lamp was linearly polarized and illuminated the metasurface through a microscope objective. The reflected light from the objective back focal plane was imaged onto a spectrograph/CCD couple with a tube lens and Bertrand lens pair. An analyzer was used before the spectrograph to select specific components of the optical transfer function tensor.

272 S3.2 Spectrometry

273 The normal-incidence and angle-dependent spectroscopy experiments are detailed in the
 274 Methods section of the main article. Here, schematics of their experimental configurations
 275 are shown in Figs. S12 and S13.

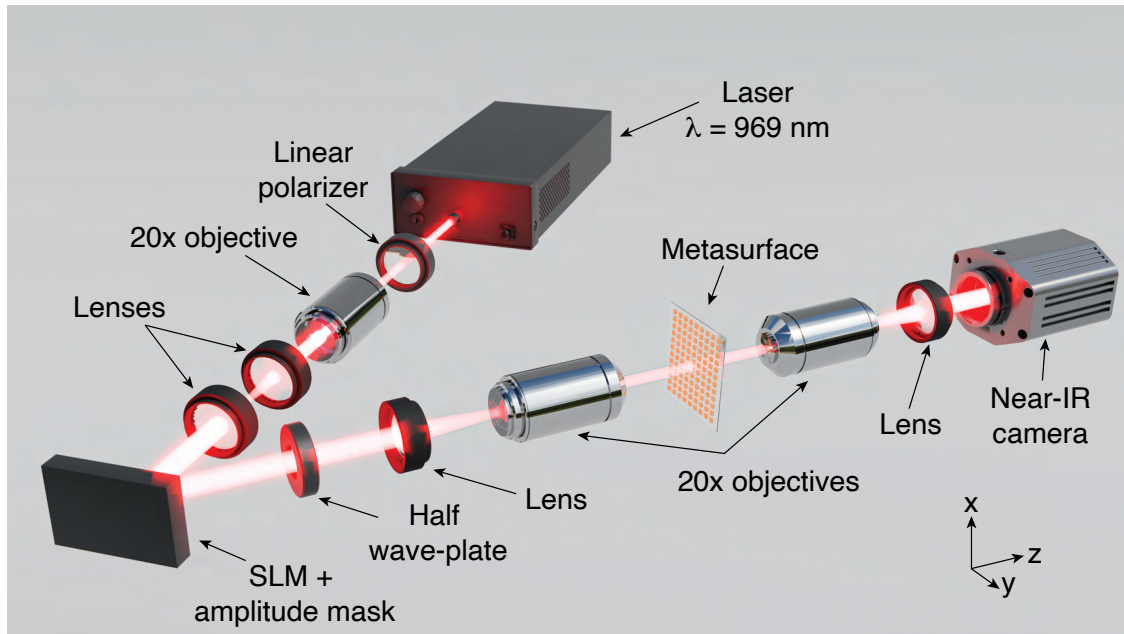


Figure S14: **Experimental configuration for imaging involving a spatial light modulator.** The light from a super-continuum source was linearly polarized and collimated by a microscope objective and two lenses. The lenses expanded the beam to fill the aperture window of the SLM. An amplitude mask was placed in front of the SLM. The light reflected by the SLM was focused into a microscope objective by a lens. The microscope objective produced a small collimated beam containing a de-magnified image of the SLM aperture. The metasurface was placed in the image plane. A half wave-plate was placed before the lens to change the polarization. A microscope objective and lens relayed a magnified image onto a camera.

276 **S3.3 Imaging with a spatial light modulator**

277 The experimental imaging results involving the SLM presented were obtained with the con-
 278 figuration illustrated in Fig. S14. This schematic is also shown in Fig. 3 of the main
 279 article.

280 **S3.4 Biological microscopy**

281 The experimental biological imaging results with the metasurface presented in the main
 282 article were obtained with the configuration illustrated in Fig. S14. This schematic is also
 283 shown in Fig. 4 of the main article.

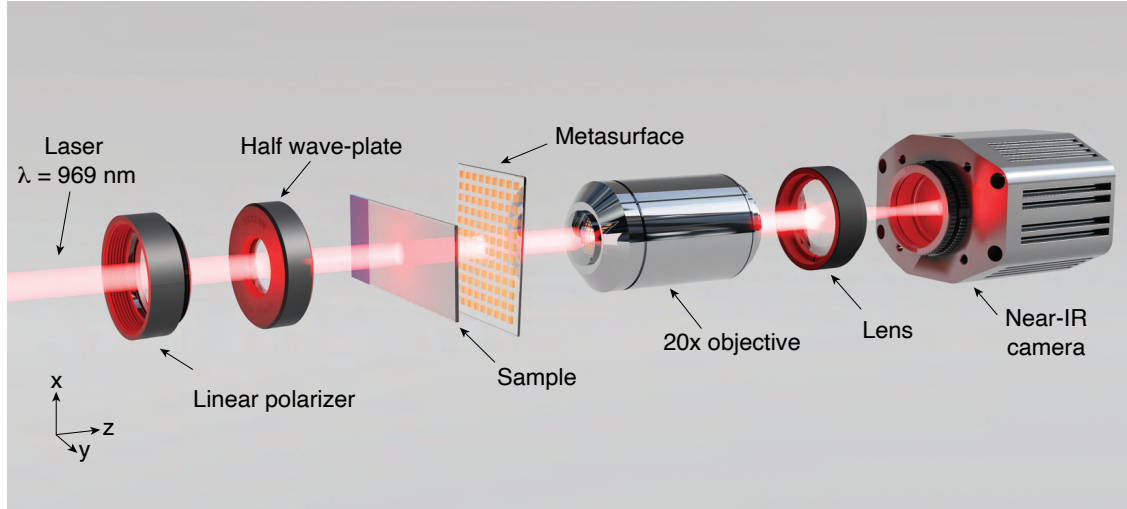


Figure S15: **Bio-imaging configuration.** The light from a super-continuum source was linearly polarized and a half wave-plate was used to control the polarization. The light illuminated a sample and the metasurface was placed after the sample. A microscope objective and lens relayed a magnified image onto a camera.

284 **S4 Additional experimental data**

285 **S4.1 Metasurface fabrication**

286 A flowchart of the fabrication process and pictures of the metasurface are given in Fig. S16.
 287 The metasurface was fabricated on a 10 mm-thick glass substrate that was 15 mm by 15 mm
 288 in size. A thin 23 nm layer of indium tin oxide (ITO) was coated onto the glass substrate
 289 to be used as a conducting protector for the electron beam lithography process. Similarly,
 290 a thin 10 nm layer of aluminium oxide (Al_2O_3) was coated onto the silicon to be used as a
 291 hard protective mask for the etching process.

292 **S4.2 Optical characterization**

293 The angle-dependent spectroscopy experiments were performed with the back focal plane
 294 imaging configuration depicted in Fig. S13 and detailed in the Methods section of the
 295 main article. The metasurface was oriented such that the angular range would be along
 296 the plane of incidence defined by the long axis of the metasurface. The results (Fig. S17)

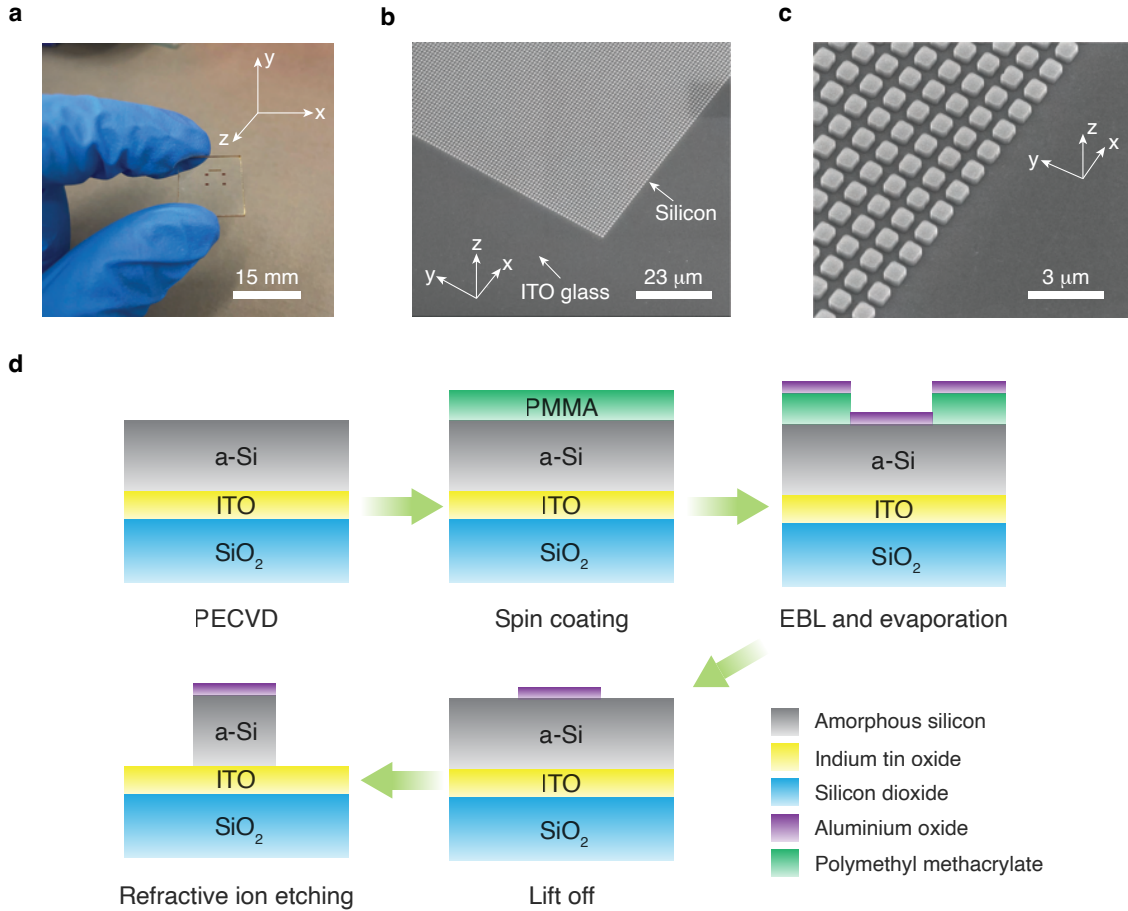


Figure S16: **Fabrication of the metasurface.** (a) A photo of the metasurface fabricated onto a coverslip. (b),(c) Scanning electron microscope images of the metasurface. (d) A flowchart of the fabrication process. Plasma-enhanced chemical vapor deposition is abbreviated to PECVD.

297 show the reflectance counts as a function of the wavelength and angle for input x - and
 298 y -polarized illumination. The former shows strong reflection at normal incidence at the
 299 operating wavelength, which decreases in strength as the angle increases. Meanwhile, the
 300 latter has a relatively low reflection. Plots of the line profiles along the line segments in Fig.
 301 S17 are given in Fig. 2b-ii of the main article in the form of transmission amplitude data.

302 S4.3 Performance metrics

303 The experimental performance of the metasurface was quantified through the metrics pre-
 304 sented in Table S2. These included the transmittance, reflectance, quality factor, numerical
 305 aperture, angular response, processing efficiency and the switching contrast. The results are

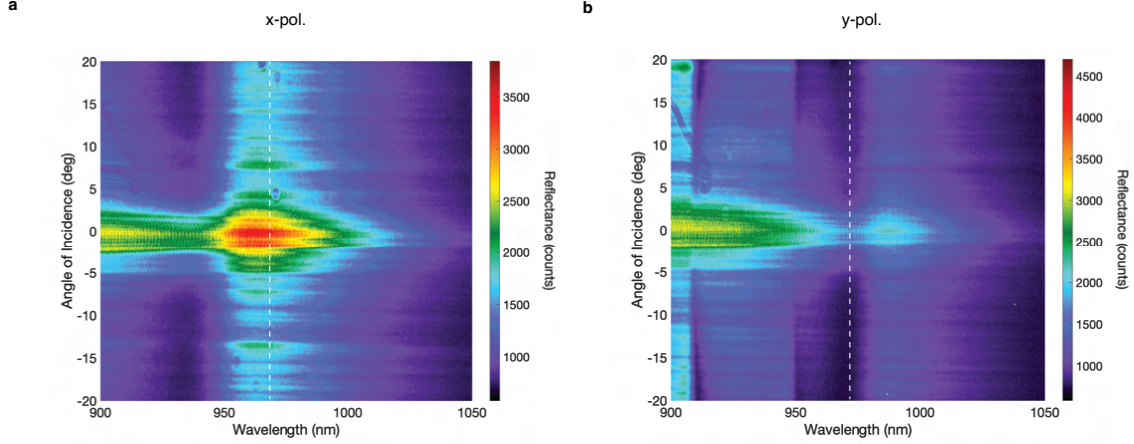


Figure S17: **Angle-dependent spectroscopy via back focal plane imaging.** (a) 2D heat map of the reflectance counts from the metasurface as a function of the wavelength and angle of incidence for px -polarization. (b) Same as a but for y -polarization. The white dashed lines indicate the operating wavelength.

Table S2: **Experimental performance metrics of the metasurface.** The experimental performance metrics obtained at the operating wavelength of 969 nm.

Quantity	Label	Formula	Value
Transmittance	T	$ E_t/E_0 ^2$	≥ 0.096
Reflectance	R	$ E_r/E_0 ^2$	≤ 0.931
Quality factor	Q	$\lambda/\Delta\lambda$	19.29
Numerical aperture	NA	$(k_x^{\max} - k_x^{\min})/k_0$	≤ 0.17
Angular response	Θ	$\Delta\lambda/\lambda$	0.05
Processing efficiency	η	$ H_{xx}(k_x^{\max}, 0) $	78%
Switching contrast (amplitude)	δ	$H_{yy}(0, 0) - H_{xx}(0, 0)$	60%
Switching contrast (transmittance)	Δ	$T_y - T_x$	71%

306 tabulated in Table S2 and can be compared to the simulations in Table S1.

307 S4.4 Imaging experiments

308 The multi-modal microscopy experiments involving the SLM were performed with the three
 309 different imaging targets set out in section S2.4. The imaging results with the ‘Amplitude’
 310 and ‘Phase’ words in the imaging target were presented in Fig. 3 of the main article. The
 311 imaging results of the red blood cell are given in Fig. S18 and the results of the Jurkat cell
 312 are given in Fig. S19.

313 The red blood cell (Fig. S18b) and Jurkat cell (Fig. S19b) were visualized in the images

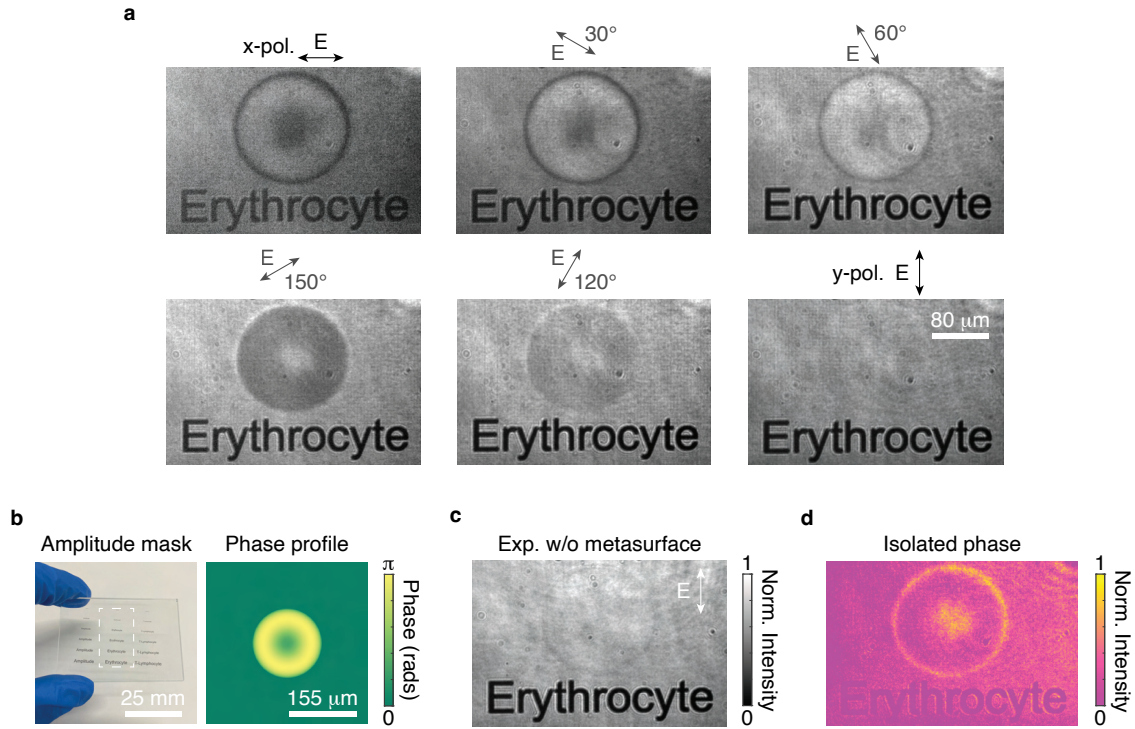


Figure S18: **Tunable multi-modal microscopy experiments of samples produced by a spatial light modulator - red blood cell.** (a) The experimental images obtained with the metasurface for different polarization states of the illumination at the operating wavelength. (b) The input imaging target included an amplitude mask and a phase profile on the spatial light modulator. (c) The experimental image obtained in the absence of the metasurface. (d) The image obtained by subtracting the image obtained with x -polarized illumination from the image obtained with y -polarized illumination.

314 obtained under x -polarized illumination (Figs. S18a and S19a). The contrast of these
 315 features had a pseudo-3D appearance. On the other hand, the words ‘Erythrocyte’ (Fig.
 316 S18b) and ‘T-Lymphocyte’ (Fig. S19b) were visible in all of the images obtained in the
 317 experiment (Figs. S18a and S19a), independent of the polarization. In particular, only these
 318 features were visible in the images obtained under y -polarization. These images were similar
 319 to the images taken in the absence of the metasurface (Figs. S18c and S19c). The images
 320 were combined to qualitatively isolate the phase contrast by subtracting the images obtained
 321 with x -polarization from those obtained with y -polarization (Figs. S18d and S19d).

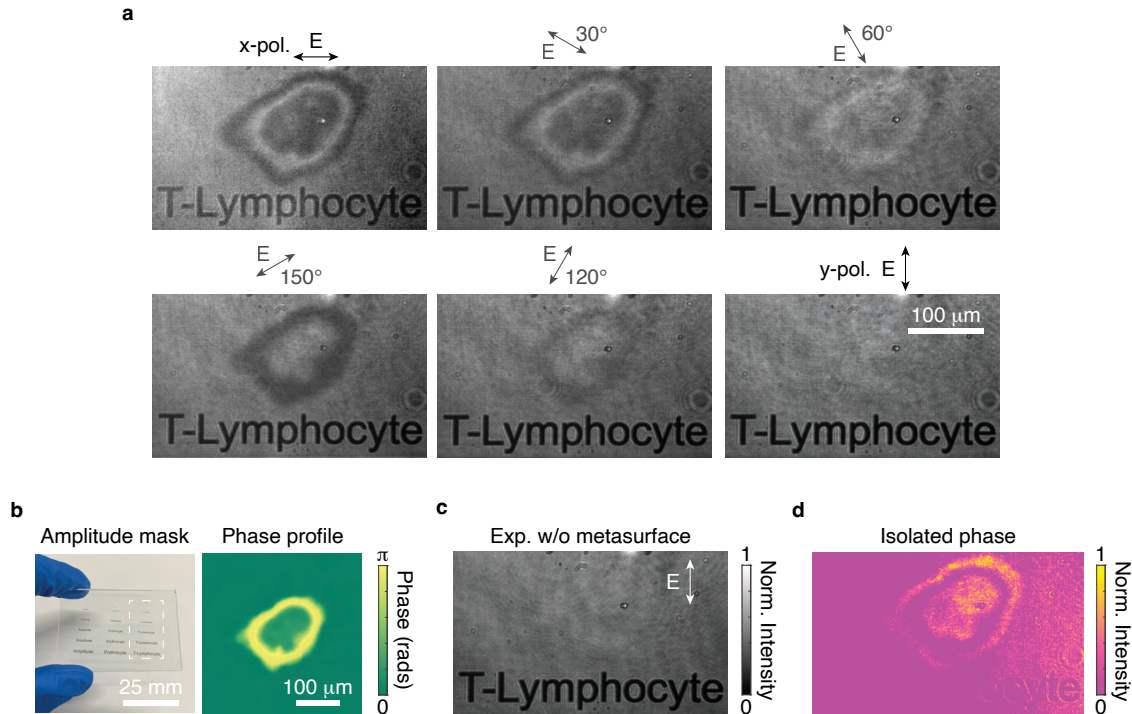


Figure S19: **Tunable multi-modal microscopy experiments of samples produced by a spatial light modulator - Jurkat cell.** (a) The experimental images obtained with the metasurface for different polarization states of the illumination at the operating wavelength. (b) The input imaging target included an amplitude mask and a phase profile on the spatial light modulator. (c) The experimental image obtained in the absence of the metasurface. (d) The image obtained by subtracting the image obtained with x -polarized illumination from the image obtained with y -polarized illumination.

322 S4.5 Biological imaging

323 As discussed in the main article, the thickness of the breast tissue sample was a challenge for
 324 the imaging modalities used in the experiments. The metasurface and the DIC microscope
 325 were capable of highlighting the architectural structure within the tissue, even at the higher
 326 thickness provided by the microtomy blade sectioning of the whole tissue blocks. This
 327 capacity can allow for the identification of normal architectural patterns within the tissue
 328 and those which are abnormal, e.g. tumours often form aberrant architectural structural
 329 arrangements. However, identifying more complex structures or lower order cellular detail
 330 is uncertain, as the imaged area included only a small number of structures in a simple and
 331 benign arrangement.

332 Instead, a more ideal application would be the preparation of cellular material rather
333 than formalin-fixed, paraffin embedded in-situ tissue that requires a thicker tissue sample.
334 In this case, the imaging samples would be generated by smearing fresh tissue to directly
335 transfer individual and clusters of cells onto a glass slide, rather than an entire section of
336 tissue. This produces a thinner sample with cells juxtaposed on a background slide, rather
337 than remaining embedded in their native tissue environment. These thinner samples would
338 provide a greater differential between individual and groups of cells and the background glass
339 slide. Furthermore, it may facilitate a better generation of cellular level imaging data.

340 **S4.6 Experimental videos**

341 Four experimental videos are included as supporting material. The first (Video S1) is a
342 recording of an experiment made on the polarization switching ability of the metasurface.
343 By using the experimental configuration detailed in the ‘Multi-modal microscopy - biological
344 samples and polarization switching’ sub-section of the Methods section of the main article,
345 an image of the metasurface was captured by a camera under normally incident illumination
346 at the operating wavelength. The video shows how the performance of the metasurface
347 changes as a function of the polarization.

348 The second video (Video S2) is a recording of an imaging experiment with the meta-
349 surface. By using the experimental configuration detailed in the ‘Multi-modal microscopy
350 - spatial light modulator’ sub-section of the Methods section of the main article, contrast
351 related to the phase profile of a Jurkat cell was visualized by the metasurface. The phase
352 profile disappears as the polarization of the illumination was changed.

353 The third (Video S3) and fourth (Video S4) videos are recordings of some of the exper-
354 imental tests made for imaging *C. elegans* with the metasurface. The videos show how the
355 nematodes appear with and without the metasurface, as well as a live nematode moving in
356 the sample. The latter demonstrates the capacity for the metasurface to be used for dynamic
357 monitoring of samples.

References

- (1) Wesemann, L.; Davis, T. J.; Roberts, A. Meta-optical and Thin Film Devices for All-optical Information Processing. *Applied Physics Reviews* **2021**, *8*, 031309.
- (2) Goodman, J. W. *Introduction to Fourier Optics*; McGraw-Hill, 1996.
- (3) Terekhov, P. D.; Babicheva, V. E.; Baryshnikova, K. V.; Shalin, A. S.; Karabchevsky, A.; Evlyukhin, A. B. Multipole analysis of dielectric metasurfaces composed of nonspherical nanoparticles and lattice invisibility effect. *Physical Review B* **2019**, *99*, 045424.
- (4) Mie, G. Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen. *Annalen der Physik* **1908**, *330*, 377.
- (5) Bohren, C. F.; Huffman, D. R. *Absorption and Scattering of Light by Small Particles*; John Wiley & Sons, 1983.
- (6) Mühlig, S.; Menzel, C.; Rockstuhl, C.; Lederer, F. Multipole Analysis of Meta-atoms. *Metamaterials* **2011**, *5*, 64–73.
- (7) Fruhnert, M.; Fernandez-Corbaton, I.; Yannopapas, V.; Rockstuhl, C. Computing the T-matrix of a Scattering Object with Multiple Plane Wave Illuminations. *Beilstein Journal of Nanotechnology* **2017**, *8*, 614–626.
- (8) Shi, Z.; Zhu, A. Y.; Li, Z.; Huang, Y.-W.; Chen, W. T.; Qiu, C.-W.; Capasso, F. Continuous angle-tunable birefringence with freeform metasurfaces for arbitrary polarization conversion. *Science Advances* **2020**, *6*, eaba3367.
- (9) Evans, E.; Fung, Y.-C. Improved measurements of the erythrocyte geometry. *Microvascular Research* **1972**, *4*, 335–347.

- 380 (10) Schneider, U.; Schwenk, H.-U.; Bornkamm, G. Characterization of EBV-genome nega-
381 tive “null” and “T” cell lines derived from children with acute lymphoblastic leukemia
382 and leukemic transformed non-Hodgkin lymphoma. *International Journal of Cancer*
383 **1977**, *19*, 621–626.
- 384 (11) Zhang, Q.; Zhong, L.; Tang, P.; Yuan, Y.; Liu, S.; Tian, J.; Lu, X. Quantitative
385 refractive index distribution of single cell by combining phase-shifting interferometry
386 and AFM imaging. *Scientific Reports* **2017**, *7*, 2532.