Leaky-wave metasurfaces for integrated photonics

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Metasurfaces have been rapidly advancing our command over the many degrees of freedom of light; however, so far, they have been mostly limited to manipulating light in free space. Metasurfaces integrated on top of guided-wave photonic systems have been explored to control the scattering of light off-chip with enhanced functionalities—namely, the point-by-point manipulation of amplitude, phase or polarization. However, these efforts have so far been limited to controlling one or two optical degrees of freedom at best, as well as device configurations much more complex compared with conventional grating couplers. Here we introduce leaky-wave metasurfaces, which are based on symmetry-broken photonic crystal slabs that support quasi-bound states in the continuum. This platform has a compact form factor equivalent to the one of grating couplers, but it provides full command over the amplitude, phase and polarization (four optical degrees of freedom) across large apertures. We present devices for phase and amplitude control at a fixed polarization state, and devices controlling all the four optical degrees of freedom for operation at a wavelength of 1.55 μm. Merging the fields of guided and free-space optics through the hybrid nature of quasi-bound states in the continuum, our leaky-wave metasurfaces may find applications in imaging, communications, augmented reality, quantum optics, LIDAR and integrated photonic systems.
Recent years have seen a rapidly growing interest in incorporating metasurface principles into integrated photonics\cite{32,33} and, very recently, in generating wavefronts from one-dimensional\cite{35,36} or two-dimensional\cite{37,38} in-plane guided modes. This capability is of great interest to the broader optics community, opening opportunities to control the off-chip emission of customized free-space wavefronts, as well as leveraging the on-chip manipulation of light based on the commercially maturing field of photonic integrated circuits (PICs). The customizability of a metasurface-based replacement for GCs offers exciting opportunities for optical communications, augmented reality, quantum optics and LIDAR. However, so far, the presented approaches offer only partial solutions, not capable of fully controlling the coupling of guided waves to far-field radiation. Typically, only one\cite{32–34} or two\cite{35–38} optical degrees of freedom have been manipulated at once for a given guided wave, limiting applications to scalar fields (Supplementary Table 1 lists the recent progress made in this context).

Additionally, contrary to corrugated structures typically seen in GCs used in integrated photonics (Fig. 1a,b), the structures proposed so far are composed of a waveguiding layer and a metasurface as two separate objects (Fig. 1c,d), which hinders integrability, scalability and compactness. In early examples, separated metasurface and GC layers were used\cite{35}, whereas in more recent examples, the metasurface was placed in the evanescent field of the guided mode to both scatter light and manipulate its phase profile. Both metallic\cite{36} and dielectric\cite{37} structures have been explored, introducing either optical loss or high-aspect-ratio dielectric structures typical of metasurface approaches. Adding such a lossy or high-aspect-ratio metasurface layer on top of existing waveguiding structures complicates its implementation compared with conventional GCs. Additionally, so far, these efforts have been limited to small surface emission apertures. These factors hinder the adoption of this approach in PICs. In contrast, a device configuration featuring the compact form factor typical of GCs, and capable of robust, sub-wavelength control of all the four degrees of freedom of light (A, Φ, ψ, χ) introduces a generalization (and where appropriate, replacement) of GCs, advancing existing approaches in both form and function.

In this work, we introduce a leaky-wave metasurface (LWM) platform based on weakly corrugated, symmetry-broken photonic crystal slabs, which supports a quasi-bound wave capable of arbitrarily tailoring the scattered field (A, Φ, ψ, χ) with subwavelength resolution (Fig. 1e,f). LWMs inherit the form of GCs and greatly improve the functionality of metasurface-on-waveguide solutions. We experimentally implement the proposed concepts in the near-infrared spectral region (near λ = 1.55 µm) based on a silicon nitride (Si,N) and polymer system, where nanostructured polymer zones on an unpatterned Si,N thin film define both rib waveguides and LWMs. The design principles are rooted in quasi-bound states in the continuum\cite{44,45} and diffractive non-local metasurfaces\cite{46,47}, enabling a rational design approach with largely independent mapping of four geometric parameters to the four optical degrees of freedom. To demonstrate the flexibility of our platform, we realize the focused emission of a desired linear polarization (with wavelength-tuned scanning of the focal spot), a vortex beam generated in concert with a Gaussian reference beam, a two-image hologram encoded in the amplitude and phase of a single polarization, a four-image hologram encoded in the amplitudes and phases of two orthogonal polarizations, and a converging Poincaré beam\cite{48}.
Operating principles and metasurface design

The key operating principle of our LWM platform is the deliberate perturbation of a guided mode supported by a periodic structure with subwavelength pitch (that is, a bound wave under the light line) into a quasi-bound wave (above the light line). As sketched in Fig. 1f, a guided mode incident from a waveguide couples to a bound wave in the subwavelength periodic structure, which then leaks into free space due to a period-doubling perturbation47. As a proof of principle, we use the configuration shown in Fig. 2a,b based on a rib waveguide and a metasurface defined within a thin layer of polymer (n = 1.48) sitting on a silicon dioxide substrate (n = 1.44) (Methods provides the detailed geometrical parameters). The metasurface in its unperturbed state (Fig. 2c) is a two-dimensional photonic crystal composed of an oblique lattice of circular holes with pitches $a_x$ and $a_y$; it supports a bound wave traveling in the $-y$ direction, whose effective wavelength is approximately $\lambda_{\text{eff}} = 2a_x$. Two independent perturbations are applied to the top pair of circular holes (Fig. 2d, Perturbation 1) and to the bottom pair of circular holes (Fig. 2e, Perturbation 2). These perturbations double the effective lattice pitches to $2a_x$ and $2a_y$, and alter the lattice from oblique to rectangular (Supplementary Section 2), modifying the first Brillouin zone of the unperturbed lattice (Fig. 2f) and its band diagram (Fig. 2g) into the zone-folded versions (Fig. 2h,i). The resulting band structure supports transverse-magnetic (TM) modes near $\lambda_{\text{eff}} = 2a_y$ in the form of a Dirac point at normal incidence, allowing operation anywhere at or near normal to the device plane48. We note that an undesirable flat band also arises, degenerate with the Dirac point when $a_x = a_y$, which may be blueshifted or redshifted by detuning from this condition, if desired (Supplementary Section 3). In this way, the deliberate engineering of the symmetry-breaking perturbation (Fig. 2) determines both if and how the wave leaks into free space, at or near the device normal and pixel by pixel across the LWM aperture.

The dual-perturbation scheme (Fig. 2d,e) enables the independent control of the real and imaginary parts of the scattered light, which together confer complete command over the surface emission: $(A, \Phi, \psi, \chi)$. Here we choose the fundamental TM guided mode (Fig. 2b), which—once coupled into the unperturbed subwavelength lattice—is decomposed into its real and imaginary components (Fig. 2c). Each of these components of the travelling TM wave (characterized in the $y$ direction by $e^{-ik_y}$) is a standing wave of either even or odd parity in the $x$ direction (that is, cosine or sine). These standing waves abide by the selection rules for scattering near the device normal, determining which polarization (if any) couples to free space due to the symmetries broken by the perturbation44. The real component is bound except in the presence of Perturbation 1, where the top pair of circles are perturbed into ellipses oriented 90° relative to one another (Fig. 2d, dashed boundaries). However, Perturbation 1 does not affect the imaginary component, which is symmetry-protected due to its...
is a bound wave due to the absence of perturbation. This topological

The behaviour of a meta-unit can be analytically modelled in combination with full-wave simulations (Methods). Figure 3a shows two geometric degrees of freedom, \( \delta_1 \) and \( \delta_2 \), which determine the sign and strength of each perturbation and hence the signed magnitude of the real and imaginary components of the scattered light. Figure 3b,c shows the amplitude and phase of the scattered light \( y \)-polarized in this case), respectively. At the origin \( (\delta_1 = \delta_2 = 0) \), a singularity is observed in the phase, corresponding to a null in the scattering amplitude, that is, a bound wave due to the absence of perturbation. This topological feature is a manifestation of the polarization-agnostic geometric phase recently demonstrated to control Fano resonances in non-local metasurfaces\(^4\). Here we leverage this principle to enable LWMs with complete PA control of any polarization. To produce scattered light with other polarization states, the orientation angles \( \alpha_1 \) and \( \alpha_2 \) of the ellipses may be varied (Fig. 3d). Figure 3e,f shows elliptical parameters \( \psi \) and \( \chi \) of the scattered light as a function of \( \alpha_1 \) and \( \alpha_2 \), with example polarization states drawn for reference; between the dashed contours, arbitrary elliptical polarization states are possible. Collectively, by varying the geometric parameters \( (\delta_1, \delta_2, \alpha_1, \alpha_2) \), we can arbitrarily specify the scattered state \( (A, \Phi, \psi, \chi) \). The mapping between these parameter spaces, including fine adjustments based on full-wave simulations, are discussed in Methods. As a result, we obtain a semi-analytical library of meta-units for use in populating an LWM that—on excitation with a guided wave—produces free-space radiation with the desired spatial profiles of amplitude, phase and polarization.

Finally, the PA distributions of the guided portion of the quasi-bound wave must be accounted for when populating the LWM with meta-units targeting a specific device function (Methods). For instance, Fig. 4a shows a target PA profile producing a focused beam and Fig. 4b shows the mode-corrected PA profile, adjusted based on the guided mode depicted in Fig. 4c. Hence, targeting \( y \)-polarized light, Fig. 4d,e shows the resulting profiles of \( \delta_1 \) and \( \delta_2 \). The LWM design was then fabricated using electron-beam lithography and characterized in the near-infrared spectral region (Methods). An example photograph and a scanning electron micrograph of the fabricated devices are shown in Fig. 4f,g.

**PA control**

We experimentally demonstrate the ability of our LWM platform to generate custom PA wavefronts, choosing meta-unit motifs with fixed angles \( \alpha_1 \) and \( \alpha_2 \) such that the wavefronts are linearly polarized. For \( y \)-polarized surface emission, we choose \( \alpha_1 = \alpha_2 = 0^\circ \); whereas for \( x \)-polarized surface emission, we choose \( \alpha_1 = \alpha_2 = 45^\circ \) (Fig. 3e). Figure 5 shows four examples of LWMs, demonstrating focusing, generation of orbital angular momentum (OAM), PA holography and generation of a kagome lattice.

First, Fig. 5a shows a schematic of an LWM generating a converging beam in the surface-normal direction. As shown in Fig. 4a, a Gaussian envelope is applied to the device’s amplitude profile, and the phase profile of a metalens is encoded to focus light at a target focal length of \( f = 2 \text{ mm} \) (numerical aperture (NA) = 0.1). Longitudinal cross sections of the beam are shown in Fig. 5b,c, at \( \lambda = 1,530 \text{ nm} \), whereas a transverse cross section at the focal plane is shown in Fig. 5d, where a focal spot is observed with full-width-at-half-maximum values of \( w_x = 10.0 \pm 0.3 \mu \text{m} \) in the \( x \) direction and \( w_y = 9.1 \pm 0.1 \mu \text{m} \) in the \( y \) direction. These values are in good agreement with diffraction-limited operation, with simulated values \( w_x = 9.1 \mu \text{m} \) and \( w_y = 9.4 \mu \text{m} \) (Fig. 5d, insets). Images of the focal plane at various operating wavelengths from 1,520 to 1,580 nm are shown in Fig. 5e. The position of the focal spot along the \( y \) direction shifts linearly with respect to the wavelength, following the band diagram (Fig. 2i) with dispersion \( \frac{d\Phi}{d\lambda} = 1.2 \times 10^{-3} \text{ rad nm}^{-1} \). Measurements
confirming the linearly polarized radiation of this device are shown in Supplementary Section 7.

Next, Fig. 5f shows a schematic of an LWM generating a vortex beam with OAM order $\ell = 2$, in tandem with a tilted wave with a Gaussian profile that serves as an interferometric reference beam (encoded in the complex near field shown in Fig. 5g). An image taken at $z = 2$ mm shows the interference of the two beams (Fig. 5h), where a characteristic fork pattern with two branches is formed (confirming the OAM order), whereas an image taken at $z = 10$ mm shows the separation of the two beams (Fig. 5i). As another example, Fig. 5j demonstrates a two-image holographic LWM encoded by the two degrees of freedom inherent in a PA metasurface (the complex near field shown in Fig. 5k). The first image—the CUNY logo—is applied as the amplitude profile of the hologram, whereas the second image—the Columbia Engineering logo—is encoded in the phase profile of the hologram (using the Gerchberg–Saxton algorithm) such that the logo is reconstructed at a distance of $z = 1$ mm (NA = 0.2). Images taken at the LWM plane ($z = 0$ mm) and the holographic image plane ($z = 1$ mm) are shown in Fig. 5l and Fig. 5m, respectively.

Finally, as a demonstration of the polarization control of our platform, Fig. 5n depicts an LWM producing a kagome lattice via the complex near-field distribution shown in Fig. 5o (Fig. 5p shows the central region of this distribution). Here the selection rules for the case of $\alpha_1 = \alpha_2 = 45^\circ$ forbids emission to y polarization, but allows emission to x polarization. The measured result at a plane $z \approx 0.5$ mm away from the LWM (effective NA = 0.37) is shown in Fig. 5q. Additional devices are reported in Supplementary Sections 7 and 8, including an x-polarized Fresnel lens, a device generating radially polarized surface emission and an x-polarized two-image hologram to demonstrate complete mastery over linear polarization. The evolution of optical intensity distributions from the LWM plane to the holographic image plane is shown in Supplementary Section 10.

**Vector-beam generation**

Next, all the four geometric degrees of freedom (\(\delta_1, \delta_2, \alpha, \alpha_2\)) are utilized to realize simultaneous PA control for the two orthogonal polarization components (that is, the PA profile of a vector beam). Figure 6a,b shows a schematic of the four-image holographic LWM, extending the scheme shown in Fig. 5j–m. Images of the letters ‘\(\psi\)’ and ‘\(\chi\)’ are applied to the amplitude profiles of the y and x polarization components of the scattered field, whereas the phase profiles at the two orthogonal polarizations encode the letters ‘\(A\)’ and ‘\(\Phi\)’, respectively, for reconstruction at a distance of $z = 1$ mm (Fig. 6a,b). Images taken at the holographic image plane ($z = 1$ mm) and LWM plane ($z = 0$ mm) for y polarization are shown in Fig. 6c and Fig. 6d, respectively; Fig. 6e,f depicts the same data for x polarization.

Finally, Fig. 6g shows a schematic of an LWM generating a focused Poincaré beam with the minimum waist size at a distance of $z = 2$ mm (NA = 0.1). Here we implement the Poincaré beam as the superposition of a focused left-circularly polarized (LCP) Gaussian beam and a focused right-circularly polarized (RCP) vortex beam with $\ell = 1$, so that a transverse cross section of the beam reveals all the polarization states over the Poincaré sphere (Fig. 6g). The four optical degrees of freedom that we control in this specific demonstration are the PA profiles of the LCP and RCP states. Figure 6h shows the measured intensity distributions at a distance of $z = 2$ mm and at the six characteristic polarization states, in good agreement with the simulated results (Fig. 6i). The detailed near-field and geometry profiles of the reported devices are summarized in Supplementary Section 9.

**Outlook and conclusions**

Compared with other techniques, our approach confers a number of advantages originating from the period-doubling perturbation, which exclusively introduces coupling to free space—the mode is otherwise bound. This feature is compatible with large-aperture fields, and here we demonstrated surface emission from integrated devices with a linear dimension that is $>250\mu$m. Large-aperture (millimetre scale and above) fields are highly desirable in a number of applications due to their small divergence angles in the far field. At the same time, the lattice supports a one-dimensional zone-folded Dirac point, enabling operation at and near the device normal (broadside emission), a feature precluded by the parabolic band structure of modes employed in conventional GC designs. Most importantly, the
Fig. 5 | PAL WMs for linearly polarized light.

a. Schematic of a focusing LWM.
b, c. Measured x–z and y–z cross sections showing focused emission from the LWM at λ₀ = 1,550 nm, with a designed focal length of f = 2 mm.
d. Measured x–y cross section at the focal plane for λ₀ = 1,530 nm, with x and y linecuts compared with the simulated responses based on diffraction-limited behaviour.
e. Measurement of the focal plane at seven selected wavelengths, demonstrating steering in the y direction, following the leaky-wave dispersion.
f, g. Schematic of an LWM producing an OAM beam with ℓ = 2 (f), along with a tilted Gaussian beam as a reference, via the complex near field in g excited in the direction indicated by the black arrow (the white plus marks the centre of the OAM beam emission and the black cross marks the centre of the tilted Gaussian beam).
h. Measured interference of the two beams at plane z = 2 mm, showing a characteristic forked pattern.
i. Measured emission of the OAM device at a plane z = 10 mm away from the LWM, where the OAM and Gaussian beams are separated.
j, k. Schematic of a two-image hologram (j), where the grey-scale amplitude distribution at the LWM plane serves as the first image, and a distinct holographic image is produced at the second plane based on the phase profile, collectively encoded in the complex near field in k.
l. Measured grey-scale image (CUNY logo) at the LWM plane.
m. Measured holographic image (Columbia Engineering logo) at a plane z = 1 mm away from the LWM.

All the devices generate y-polarized light, except for the kagome lattice generator, which produces x-polarized surface emission.
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meta-unit motif with two shifted rows of judiciously oriented elliptical apertures enables the simultaneous and independent control of amplitude and polarization state of both real and imaginary components of the LWM radiation: the magnitude of the period-doubling perturbation in each row controls the amplitude of each component, whereas the orientation angle of the perturbation controls the polarization state. The symmetry-driven design enables a semi-analytical mapping between the optical degrees of freedom \((A, \Phi, \psi, \chi)\) and the geometric design parameters \((\delta_1, \delta_2, \alpha_1, \alpha_2)\). Traditionally, the difficulty in constructing a meta-unit library compounds unfavourably as the number of targeted optical degrees of freedom is increased. Here, in contrast, the LWM geometry is populated in a point-by-point manner based on a set of simple equations, while achieving complete control over the vectorial field.

Building on these advantages, several improvements and extensions may be made to this platform (Supplementary Sections 11–13). In particular, future work may improve the efficiency of the approach by engineering the profile of the scattering strength along the LWM, with near-unity efficiency achievable in suitable designs\(^{53,54}\). Our symmetry-based design principle implies that applications involving a wide array of materials and frequencies may adopt this approach. For instance, RF leaky-wave antennas are well known for beamforming and scanning in the far field, but are difficult to operate at close range. Our approach may be used to create RF leaky-wave antennas that operate

Fig. 6 | Vector-beam LWMs with complete control over amplitude, phase and polarization. a,b. Schematic of an LWM producing a four-image hologram, in which two distinct two-image holograms are encoded for y (a) and x (b) polarizations. c,d. Measured y-polarized images at the holographic image (\(z = 1\, \text{mm}; c\)) and LWM plane (\(z = 0\, \text{mm}; d\)). e,f. Measured x-polarized images at the holographic image plane (\(z = 1\, \text{mm}; e\)) and LWM plane (\(z = 0\, \text{mm}; f\)). g. Schematic of an LWM producing a focusing Poincaré beam. h,i. Measured (h) and simulated (i) profiles of six characteristic polarizations at a plane \(z = 2\, \text{mm}\).
across a wide range of distances, and with distinct functionalities imparted to orthogonal polarizations, useful for polarization-division multiplexing. Similarly, in the context of PICs, although here we showed one popular materials platform based on Si,N, the design principle can be applied to silicon-on-insulator technologies. Active materials such as lithium niobate, two-dimensional materials and liquid crystals may also be incorporated, to switch on or off the symmetry-breaking perturbation or to control its magnitude. Finally, although our LWMs are composed of two-dimensional arrays of holes in a thin film, subwavelength grating waveguides composed of pillars may also be used based on the same principles.

In conclusion, we have introduced an LWM platform that generates custom vectorial fields at will, combining the functionality of metasurfaces with the compact form factor of GCs. We demonstrated the semi-analytical generation of a library of meta-units with complete command over amplitude, phase and polarization state of light with subwavelength resolution. The design principles are rooted in the symmetries of quasi-bound waves supported by high-symmetry lattices and are thus compatible with a wide range of materials platforms and frequencies. In the future, we anticipate a number of applications stemming from this approach. Our platform may be integrated with PICs for off-chip communications such as chip-to-chip communications and free-space mode-division multiplexing (for example, using OAM (Fig. 5f–i) or Poincaré beams (Fig. 6g–i)), and it may be used to generate custom cold-atom traps for quantum applications (such as kagome lattices (Fig. 5n–q)). Although our implementation employs structural birefringence as a perturbation, small changes in material birefringence (such as in liquid crystals) may achieve similar control but in a dynamic manner. In this way, our approach may also enable LIDAR systems with optically large apertures for arbitrary beamforming (including broadside emission) and beam steering (Fig. 5e), as well as novel holographic display technologies (Fig. 5j–m and Fig. 6a–f).

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41565-023-01360-z.

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Methods
Modelling and simulations of meta-units
The Jones vector response of a half meta-unit composed of one pair of ellipses, and excited by a TM slab waveguide mode approximately follows

\[
\begin{align*}
\left( \begin{array}{c} E_x \\ E_y \\
\end{array} \right) &= \delta \left( \begin{array}{c} a_x \sin 2\alpha \\ a_x \cos 2\alpha \\
\end{array} \right).
\end{align*}
\]

(1)

where \( a_x \) (or \( a_y \)) is the maximum amplitude in \( x \) (or \( y \)) polarization, which is achieved at the maximum \( \delta \) and \( \alpha = 45^\circ (\alpha = 0^\circ) \). The imbalance between \( a_x \) and \( a_y \) originates from the asymmetry between the \( x \) and \( y \) directions of the system. Here only the first-order perturbation effect is considered; in this regime, the dependence on \( \delta \) is approximately linear. If the meta-unit is instead excited by a transverse-electric slab waveguide mode, the Jones vector response will be rotated 90° due to the conversion between electric field and magnetic field, with an additional constant term in \( E_x \) to account for zeroth-order scattering.

Amplitude \( A \) and polarization orientation angle \( \psi \) of a half meta-unit can be independently controlled by geometric parameters \( \delta \) and \( \alpha \), respectively. For given target values of \( A \) and \( \psi \), the corresponding geometric parameters can be explicitly solved:

\[
\begin{align*}
\alpha &= \frac{1}{2} \arctan \left( \frac{a_y}{a_x} \tan \psi \right), \\
\delta &= \frac{A}{a_x} \cos \psi \sqrt{1 + \left( \frac{a_y}{a_x} \tan \psi \right)^2}.
\end{align*}
\]

(2)

For a full meta-unit composed of two pairs of \( p2 \) ellipses displaced by a quarter period along the propagation direction, the response is a coherent summation of the two pairs with a 90° phase difference:

\[
\begin{align*}
\left( \begin{array}{c} E_x \\ E_y \\
\end{array} \right) &= \delta_1 \left( \begin{array}{c} a_x \sin 2\alpha_1 \\ a_x \cos 2\alpha_1 \\
\end{array} \right) + i \delta_2 \left( \begin{array}{c} a_y \sin 2\alpha_2 \\ a_y \cos 2\alpha_2 \\
\end{array} \right).
\end{align*}
\]

(4)

where the first pair of ellipses (characterized by \( (\delta_1, \alpha_1) \)) contributes to the real part and the second pair of ellipses (characterized by \( (\delta_2, \alpha_2) \)) contributes to the imaginary part. For a complex target \( (E_x, E_y) \), the required geometric parameters can be solved by first calculating the amplitudes \( A_1,2 \) and polarization orientation angles \( \psi_{1,2} \) of the real and imaginary parts, respectively:

\[
\begin{align*}
A_1 &= \sqrt{\text{Re}(E_x)^2 + \text{Re}(E_y)^2}, \\
A_2 &= \sqrt{\text{Im}(E_x)^2 + \text{Im}(E_y)^2}, \\
\psi_1 &= \arctan \left( \frac{\text{Re}(E_x)}{\text{Re}(E_y)} \right), \\
\psi_2 &= \arctan \left( \frac{\text{Im}(E_x)}{\text{Im}(E_y)} \right).
\end{align*}
\]

(5)

(6)

(7)

(8)

and then using the above formulas derived for each half meta-unit:

\[
\begin{align*}
\alpha_{1,2} &= \frac{1}{2} \arctan \left( \frac{a_y}{a_x} \tan \psi_{1,2} \right), \\
\delta_{1,2} &= \frac{A_{1,2}}{a_x} \cos \psi_{1,2} \sqrt{1 + \left( \frac{a_y}{a_x} \tan \psi_{1,2} \right)^2}.
\end{align*}
\]

(9)

(10)

Finite-difference time-domain simulation results of the polarization ellipticity angle \( (\alpha) \) and polarization orientation angle \( (\psi) \) of a leaky-wave meta-unit are shown in Fig. 3c, f, where \( \alpha_1 \) and \( \alpha_2 \) are swept from 0° to 90° to cover the polarization space, and \( \delta_{1,2} \) are set according to \( \alpha_{1,2} \) to generate a flat amplitude response. A full coverage of the polarization ellipticity angle from \( \chi = +\pi/4 \) (LCP) through \( \chi = 0 \) (linear polarization) to \( \chi = -\pi/4 \) (RCP) is achieved as \( \alpha_1 \rightarrow \alpha_2 \). In this range, the dependence on \( \delta \) is approximately linear. If the meta-unit is excited by a transverse-electric slab waveguide mode, the Jones vector response will be rotated 90° due to the conversion between electric field and magnetic field, with an additional constant term in \( E_x \) to account for zeroth-order scattering.

For a full meta-unit composed of two pairs of \( p2 \) ellipses displaced by a quarter period along the propagation direction, the response is a coherent summation of the two pairs with a 90° phase difference:

\[
\begin{align*}
\left( \begin{array}{c} E_x \\ E_y \\
\end{array} \right) &= \delta_1 \left( \begin{array}{c} a_x \sin 2\alpha_1 \\ a_x \cos 2\alpha_1 \\
\end{array} \right) + i \delta_2 \left( \begin{array}{c} a_y \sin 2\alpha_2 \\ a_y \cos 2\alpha_2 \\
\end{array} \right).
\end{align*}
\]

(4)

where the first pair of ellipses (characterized by \( (\delta_1, \alpha_1) \)) contributes to the real part and the second pair of ellipses (characterized by \( (\delta_2, \alpha_2) \)) contributes to the imaginary part. For a complex target \( (E_x, E_y) \), the required geometric parameters can be solved by first calculating the amplitudes \( A_1,2 \) and polarization orientation angles \( \psi_{1,2} \) of the real and imaginary parts, respectively:

\[
\begin{align*}
A_1 &= \sqrt{\text{Re}(E_x)^2 + \text{Re}(E_y)^2}, \\
A_2 &= \sqrt{\text{Im}(E_x)^2 + \text{Im}(E_y)^2}, \\
\psi_1 &= \arctan \left( \frac{\text{Re}(E_x)}{\text{Re}(E_y)} \right), \\
\psi_2 &= \arctan \left( \frac{\text{Im}(E_x)}{\text{Im}(E_y)} \right).
\end{align*}
\]

(5)

(6)

(7)

(8)

and then using the above formulas derived for each half meta-unit:

\[
\begin{align*}
\alpha_{1,2} &= \frac{1}{2} \arctan \left( \frac{a_y}{a_x} \tan \psi_{1,2} \right), \\
\delta_{1,2} &= \frac{A_{1,2}}{a_x} \cos \psi_{1,2} \sqrt{1 + \left( \frac{a_y}{a_x} \tan \psi_{1,2} \right)^2}.
\end{align*}
\]

(9)

(10)

Device fabrication
We experimentally demonstrate LWMs at the telecommunications wavelength \( (\lambda = 1.55 \mu m) \) using a polymer–Si3N4 materials platform. The waveguide circuit and the meta-unit holes composing the metasurface are patterned in a 300 nm poly(methyl methacrylate) layer, on the top of a 300 nm Si3N4 thin film, on a SiO2 substrate. The fundamental TM guided mode is fed from a single-mode ridge waveguide via a linear taper with a tapering rate of \( \lambda / \Delta \ell = 1/12 \). An LWM device with a linear dimension of \( ~400 \mu m \) is integrated within the taper (Fig. 4f). The PA distributions in the tapered slab waveguide are non-uniform, which should be compensated for when designing the LWM PA profiles. Expanded from a single-mode waveguide through a linear taper, the slab waveguide mode can be approximated with an analytic expression:

\[
E(x, y) = E_0 A(x, y) e^{i\phi(x, y)},
\]

(11)

with

\[
A(x, y) = \sqrt{\frac{w_0}{w(y)}} \cos \left( \frac{\pi x}{w(y)} \right) e^{i\frac{\pi}{4}},
\]

(12)

\[
\phi(x, y) = \frac{2\pi}{\lambda} \left[ -n_{\text{ms}} y + n_{\text{pe}} \frac{x^2}{(L-y)} \right],
\]

(13)

where the amplitude distribution \( A(x, y) \) is formed by the collective effects of (1) waveguide widening, that is, \( w(y) = w_0 + \Delta w / \Delta \ell \times (L - y) \), where \( L = 4.800 \mu m \) is the taper length and \( y \) is the longitudinal coordinate; (2) transverse waveguide mode profile associated with the local waveguide width \( w(y) \); and (3) attenuation due to out-coupling...
from the metasurface; the phase distribution \( \phi(x, y) \) is composed of
(1) longitudinal phase accumulation in the metasurface region with
an effective modal index \( n_{ms} \approx 1.52 \) and (2) transversal phase profile in
the linear taper with an effective modal index \( n_{wg} \approx 1.55 \), approximated
by a paraxial cylindrical wave.

Finally, the devices are fabricated as follows. Si3N4 thin films with
300 nm thickness are grown via plasma-enhanced chemical vapour
deposition on a fused silica substrate of 180 μm thickness. A 300 nm
poly(methyl methacrylate) layer is spin coated and baked at 180 °C
to serve as an electron-beam resist. Electron-beam lithography (Elionix
ELS-G100) is then carried out at 100 keV and 1 nA, with a dose of
750 μC cm\(^{-2}\) and appropriate proximity effect corrections (BEAMER),
to define the waveguide boundaries and LWM patterns. A 3:1 mixture
of isopropyl alcohol and deionized water is used to develop the exposed
resist. The fabricated chip is then cleaved to expose the facet of the
narrow single-mode ridge waveguide for fibre coupling.

**Device characterization**
Near-infrared light at \( \lambda \approx 1.55 \) μm is generated by a diode laser, and
coupled into the LWM device using a lensed optical fibre with proper
polarization adjustment. The surface emission on the air side produced
by the device is collected by a \(<10 \) or \(<20 \) near-infrared objective (Mitutoyo),
passed through a polarization filter (Thorlabs) and directed
towards a near-infrared camera (Princeton Instruments).

**Data availability**
All relevant data are available within the Article and its Supplementary
Information.

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**Author contributions**
A.C.O., H.H. and N.Y. conceived the idea. H.H. and A.C.O.
mathematically modelled the devices and performed the
simulations. H.H. designed and fabricated the devices. H.H., A.C.O.,
Y.X., S.C.M., C.-C.T. and N.Y. characterized the devices. A.C.O.
and H.H. analysed the data. A.C.O., H.H., A.A. and N.Y. wrote the
manuscript. A.A. and N.Y. supervised the research.

**Competing interests**
A.C.O., S.C.M. and N.Y. are listed as inventors in a US non-provisional
patent application no. 17/110,846; in addition, H.H., Y.X., A.C.O., A.A.
and N.Y. are listed as inventors in a US provisional patent application
no. 63/342,475. Both were filed by Columbia University and are related
to the technology reported in this Article. The remaining authors
declare no competing interests.

**Additional information**
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