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Mode-matching metasurfaces: coherent reconstruction and multiplexing of surface waves

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Metasurfaces are promising two-dimensional metamaterials that are engineered to provide unique properties or functionalities absent in naturally occurring homogeneous surfaces. Here, we report a type of metasurface for tailored reconstruction of surface plasmon waves from light. The design is based on an array of slit antennas arranged in a way that it matches the complex field distribution of the desired surface plasmon wave. The approach is generic so that one can readily create more intricate designs that selectively generate different surface plasmon waves through simple variation of the wavelength or the polarization state of incident light. The ultra-thin metasurface demonstrated in this paper provides a versatile interface between the conventional free-space optics and a two-dimensional platform such as surface plasmonics.

Surface plasmon polaritons (SPPs) are coupled electromagnetic waves and charge density oscillations tightly confined at a metal-dielectric interface, which have created an appealing two-dimensional (2D) platform for designing high-performance optical components with small footprints in various applications^{1–3}, and for bridging nanophotonics with semiconductor electronics^{4,5}. Metallic surfaces patterned with subwavelength nanostructures, such as couplers^{6–8} and planar optics (prism, lenses, etc)^{9–12}, have been developed for the generation and manipulation of SPPs. These engineered surfaces, also recognized as metasurfaces, are sometimes considered as the extension of bulk metamaterials into a 2D space, exhibiting novel functionalities and properties absent in a flat surface. Recently, new types of SPPs^{13–15} have been demonstrated to possess interesting nondiffracting properties that can be promising for plasmonic manipulation of nanoparticles¹⁶ and plasmonic circuits¹⁷.

Here we report a generic design of metasurfaces that are capable of converting free-space light into an arbitrary type of SPP. Moreover, both wavelength and polarization multiplexing of SPPs can be realized by the metasurfaces in a straightforward manner, which enables selective excitation of a specific SPP mode by varying the wavelength or the polarization state of the incident light. The technique can be readily applied to create a versatile and powerful interface between a classical optical system and a 2D plasmonic platform. For instance, information carried on a wavelength-division-multiplexed (WDM) fiber communication system may be passed on to different SPP modes by means of a wavelength-multiplexing metasurface.

An SPP wave at a metal-dielectric interface is often simply described as a one-dimensional (1D) solution to the Helmholtz equation, neglecting the spatial variation in the transverse dimension. The out-of-plane electric field of such a simple monochromatic SPP wave propagating in the x -direction, for instance, can be expressed by $E_z(x, z) = Ae^{-\alpha z}e^{i\beta x}$ (considering the dielectric half-space $z > 0$)¹⁸. The

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parameter α indicates the confinement of the surface wave in the direction perpendicular to the surface, and the complex-valued propagation constant $\beta = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}$, where ϵ_m, ϵ_d are the permittivity of the metal and dielectric, respectively, and $k_0 = \omega/c$ is the wave vector in vacuum. α and β are related through $\alpha^2 + \epsilon_d k_0^2 = \beta^2$. Since the surface wave in general has a wavelength shorter than the free-space light of the same frequency, additional momentum is needed to fulfill momentum conservation for the excitation of the surface wave from free-space light. Conventionally, the condition can be met at a flat metal-dielectric interface with the help of attenuated total internal reflection from a denser optical medium (Supplementary Fig. S1a)^{19,20}. Alternatively, the additional momentum can be provided by periodic corrugations created by a metasurface, such as 1D plasmonic gratings (extended infinitely in the other direction), which provides a more compact alternative (Supplementary Fig. S1b)^{21,22}. In the latter case, the momentum matching condition

$$\text{Re}\{\beta\} = k_0 \sin \theta + m \frac{2\pi}{\Lambda} \quad (1)$$

(m is an integer number and θ is the incident angle) is achieved with the additional momentum parallel to the surface provided by the grating. By adjusting the period Λ of the grating, the approach can accommodate a wide range of incident angles, including normal incidence, where the corresponding grating period equals to the wavelength of the SPP. Based on a 2D extension of the momentum-matching condition interpreted as mode-matching in this paper, we present a generic metasurface design consisting of two-dimensional (2D) plasmonic gratings (dubbed as mode-matching plasmonic gratings (MPGs)) for the coherent reconstruction of complex 2D SPP modes, and the transverse variation is no more neglected. In addition, we also show that the mode-matching metasurface design incorporates wavelength/polarization multiplexing of SPPs inherently.

Recently, the advent of the study of SPPs has revealed more intricate transverse profiles of the surface wave^{13–15,23–27}. Examples like plasmonic Airy beams (PABs)^{13,14,23–25}, have broadened our understanding of SPPs and opened up a whole new area because of the additional degree of freedom in the transverse dimension of SPPs. For its intriguing properties, such as propagating in a diffraction-free manner and following a parabolic trajectory¹³, the PAB is chosen as an exemplary surface wave to demonstrate the principle of our mode-matching metasurfaces. PABs were first experimentally produced by a periodic phase-shifted coupling grating milled into a metal surface, where the transverse field of the surface wave was reconstructed at a specific propagation distance¹⁴. Alternatively, light can be first coupled to a 1D SPP wave, and then through in-plane diffraction from a carefully designed aperiodic array, PABs can be created²⁴. A controllable generation of PABs can be realized by projecting free-space Airy beams to a plasmonic grating with the help of a liquid-crystal spatial light modulator²³. In this paper, we show that by matching the 2D field distribution of a known SPP mode e.g. a PAB in our case, a generalized plasmonic metasurface can be devised to convert a planewave into the desired 2D surface wave directly.

Materials and Methods

The 2D distribution (at a given height above the metal-dielectric interface) of the E_z component of a PAB propagating in the x -direction is given by

$$E_z(u, v) = Ai(v - u^2 + i2au) \exp(av - 2au^2) \exp\left[i\left(uv + a^2u - \frac{2}{3}u^3\right)\right] \quad (2)$$

with the normalized coordinates defined as $u = \frac{x}{2\beta y_0^2}$ and $v = \frac{y}{y_0}$, where the parameter a measures the apodization, y_0 is a transverse scaling factor, and $Ai(\cdot)$ is the Airy function¹³. Having the amplitude and phase distributions given by Eq. 2, in our design (Fig. 1A), a series of subwavelength slits are milled through an optically opaque Ag film at places where the phase of the desired surface wave (e.g. a PAB in the example) has the same value (e.g. zero) and the amplitude is above a threshold (Fig. 1B,C). When the perforated metal film is illuminated with a *coherent* source (e.g. a laser beam) with the correct polarization, each slit acts like a tiny antenna that receives the free-space light, and radiates surface wavelets (with the maximum radiation intensity occurring in the direction along the short axis of a slit). All antennas in the film are synchronized (in phase) because of the coherence of the incident planewave. However, in order for the surface wavelets emitted by all the antennas from different locations to interfere constructively forming the desired surface wave, these synchronized antennas must be placed at the wavefronts of the target surface wave. The aperture antennas (slits) are fabricated in an Ag film using focused ion beam (FIB) milling (Fig. 1D) and the reconstructed near-field intensity distributions (Fig. 1E,F) are found to be in a good agreement with the theoretically predicted profile of the desired PAB (Supplementary Fig. S2).

Although a 1D periodic grating generates 1D SPPs (Supplementary Fig. S1B), in a more general case like the reconstruction of PABs, the wavefront of the surface wave is usually not a straight line, which implies the space-variant orientation of the wavevector (gradient of phase change)—the vectorial nature of a momentum. Hence, *locally* the design of the grating must have not only the right periodicity (as indicated in Eq. 1) but also the correct orientation (as indicated by the direction of the local wave-vector

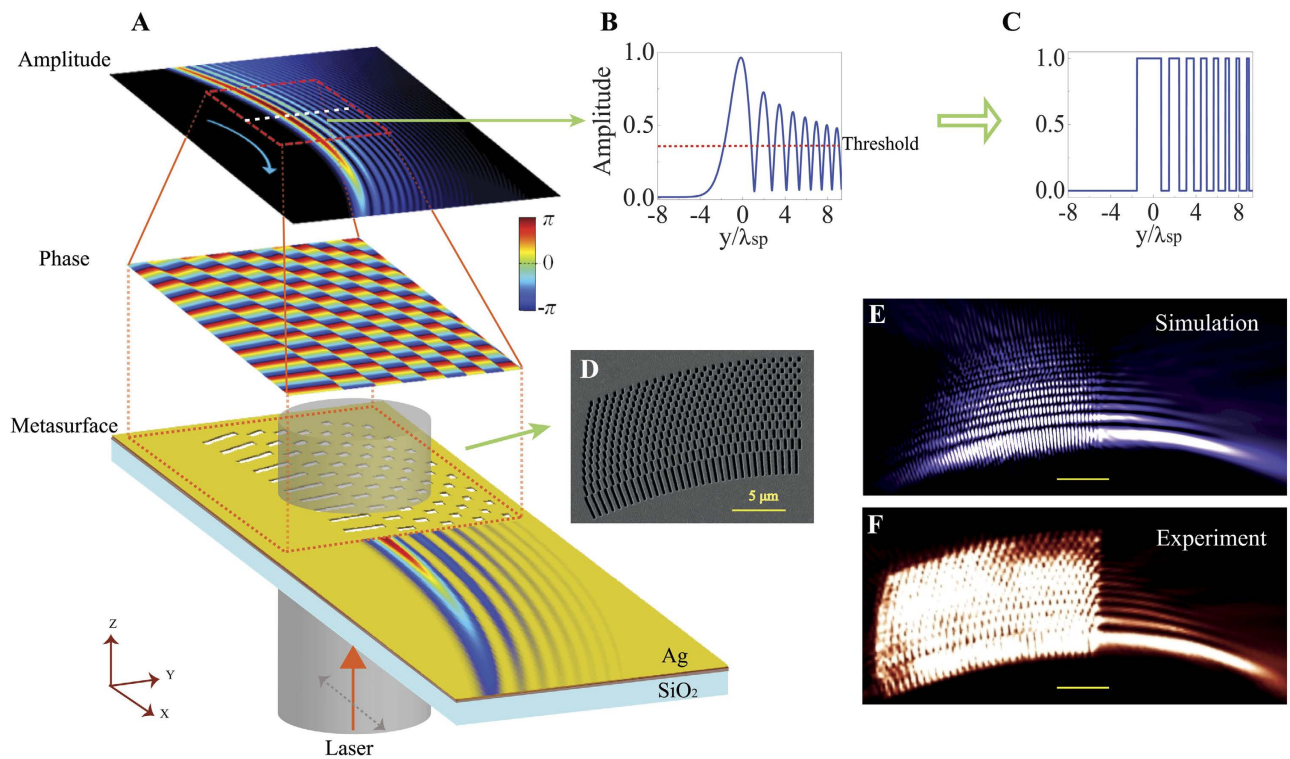


Figure 1. Mode-matching metasurface and the reconstruction of a surface wave. (A) Design of the MPG for the reconstruction of a PAB. The normalized amplitude of the 2D field distribution (E_z) of the target PAB is replaced with binary values “1” and “0”. A threshold value is chosen for the quantization process as illustrated in B & C. An optically thick Ag film (200 nm) on a transparent glass substrate is perforated by FIB milling at positions where the phase of the 2D field distribution is equal to zero, and the binary amplitude is equal to unity. The resultant pattern consists of a series of slits with the width of ~ 200 nm. When the metasurface is illuminated with a weakly focused x-polarized Gaussian laser beam (633 nm and at matching frequency with the target SPP mode) from below, the SPP wavelets excited at individual slits propagate along the surface and add up constructively everywhere since they fulfill the local momentum matching condition for the specific surface wave. As a result, the target SPP wave is observed at the boundary of the perforated area. (B) The normalized amplitude profile of the PAB at a specific propagation distance. (C) The binary amplitude profile after thresholding. (D) Scanning electron micrograph of the metasurface that is used to reconstruct the PAB ($\lambda_{sp} = 613\text{nm}$, $a = 0.02$, and $y_0 = 600\text{nm}$). (E) 2D intensity distribution of the E_z component of the reconstructed PAB obtained by full-wave calculation with the finite-difference time-domain (FDTD) method (scale bar: $5\mu\text{m}$). (F) Near-field intensity distribution of the reconstructed PAB measured by near-field scanning optical microscopy (scale bar: $5\mu\text{m}$). In principle, the mode-matching metasurfaces should excite SPPs in both directions. However, the excitation laser was slight focused by an objective lens. So the illumination on the metasurface might be tilted if the sample was not placed exactly in the center of the focal spot. The slightly tilted illumination favors one direction of the excited SPP without affecting its near-field distribution.

of the target surface wave), such that the additional momentum provided by the grating fulfills the momentum-matching condition in both the magnitude and the direction simultaneously. Therefore, a simple replication of the structure in one dimension cannot guarantee the reconstruction of a surface wave generally. A direct comparison (Supplementary Fig. S3) of the PAB reconstructed from an MPG with that from a 1D repetitive structure confirms the necessity of matching the plasmonic gratings with the *space-variant* wavefront of a propagating surface wave.

Results and Discussion

One interesting property of the mode-matching metasurfaces made of MPGs is the inherent multiplexing capability using incident angles or wavelengths. The angular multiplexing and wavelength multiplexing are usually interchangeable as shown in the momentum matching condition (Eq. 1). Because of the normal incidence configuration of the near-field scanning optical microscope (NSOM), we choose to demonstrate the wavelength multiplexing of SPPs. In Fig. 2, we show that the reconstructed SPP from a composite MPG, a metasurface consisting of several MPGs, varies with the incident wavelength. When

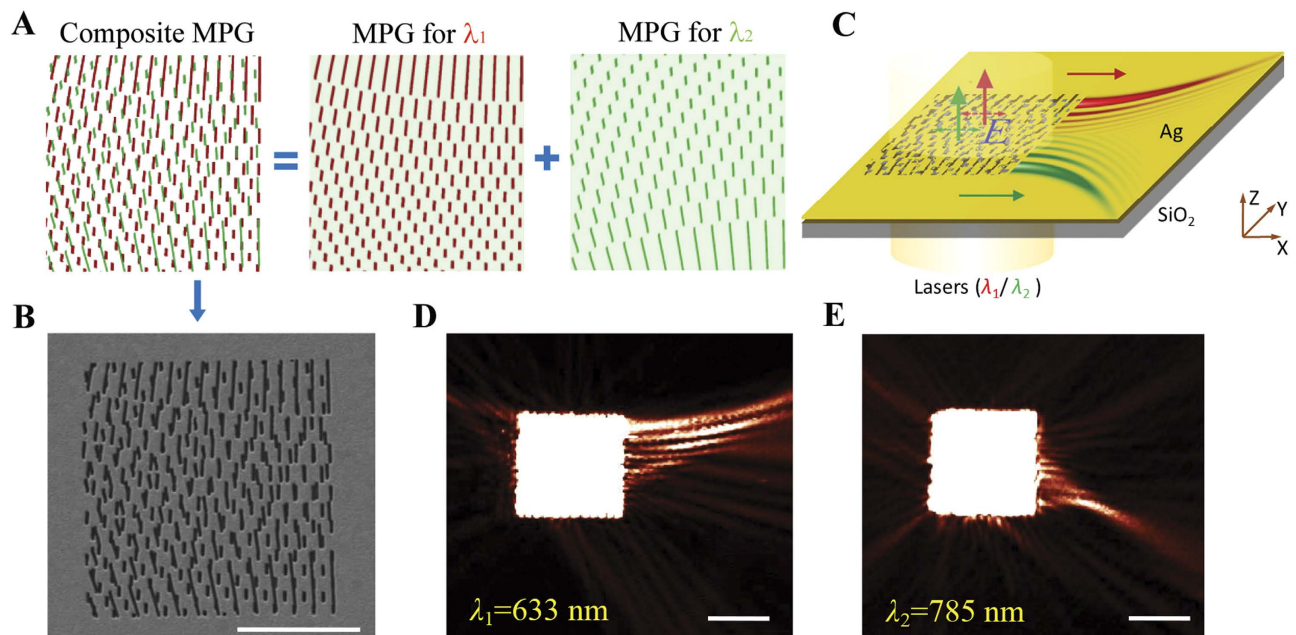


Figure 2. Wavelength-multiplexing with a mode-matching metasurface. (A) Design of the composite MPG for the reconstruction of two PABs of different effective wavelengths (613 nm and 770 nm at an Ag/air interface). The composite MPG is the superposition of two MPGs of different periodicity that are designed individually for reconstructing the two PABs. (B) Scanning electron micrograph of the metasurface for wavelength multiplexing (scale bar: $5\mu\text{m}$). (C) Two PABs are reconstructed individually under the illumination of different laser sources (633 nm and 785 nm). (D) & (E) Near-field intensity distributions (scale bar: $5\mu\text{m}$) of the two reconstructed PABs are measured by NSOM as in D ($\lambda_{sp} = 613\text{nm}$, $a = 0.02$, and $y_0 = -600\text{nm}$) and E ($\lambda_{sp} = 770\text{nm}$, $a = 0.02$, and $y_0 = 600\text{nm}$).

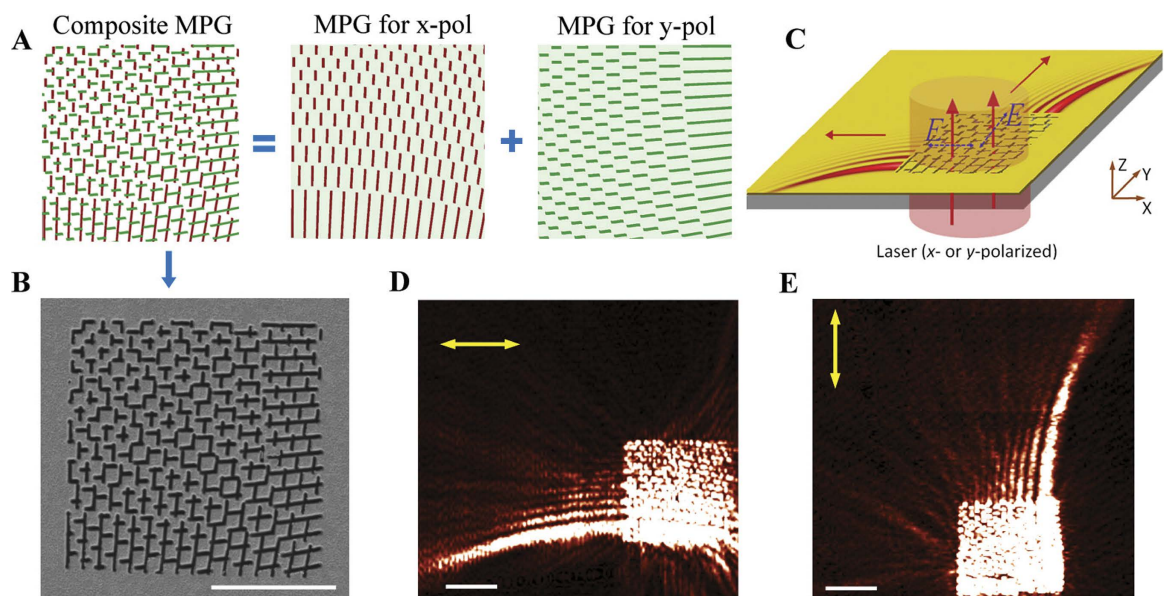


Figure 3. Polarization-multiplexing with a mode-matching metasurface. (A) Design of the composite MPG for the reconstruction of PABs at two incident orthogonal polarization states (x- and y-polarized). The composite MPG consists of two separate MPGs designed for orthogonal polarization states. (B) Scanning electron micrograph of the metasurface for polarization multiplexing (scale bar: $5\mu\text{m}$). (C) The metasurface is illuminated with a linearly polarized laser beam of 633 nm. The polarization state of the incident beam is changed by rotating a half-wave plate inserted in the optical path. (D) & (E) Near-field intensity distributions (scale bar: $5\mu\text{m}$) of the reconstructed PABs as measured in D ($\lambda_{sp} = 613\text{nm}$, $a = 0.02$, and $y_0 = -600\text{nm}$) and in E ($\lambda_{sp} = 613\text{nm}$, $a = 0.02$, and $y_0 = 600\text{nm}$) with x-polarized and y-polarized incident light, respectively. The yellow arrows indicate the polarization state of the incident light.

the metasurface is illuminated by a coherent source of an individual wavelength, only the wavelets generated by all the slits of the corresponding constituent MPG can interfere constructively as the momentum matching condition is fulfilled by the particular incident wavelength. Therefore, the change of incident wavelength would result in the reconstruction of a different SPP mode. Given the parabolic trajectory of a PAB as shown in the example, the information carried by light of various wavelengths in free space will be directed to different direction on the metasurface. The minimal separation of wavelengths is determined by the spectral response of the individual MPG, which is estimated to be a few tens nanometers in spectral width depending on the material and the specific design.

Another useful feature of the MPG-enabled metasurfaces is the capability of polarization multiplexing of SPPs. Since the constituent slits radiate SPPs at the highest efficiency when the polarization of the incident light is oriented along their short axes, the metasurface is sensitive to the polarization state of light. This intrinsic characteristic is explored in our experiment to selectively excite specific constituent MPGs in a composite MPG by varying the orientation of the linear polarization state of incident light (Fig. 3). In this case, a mode-matching metasurface is made by overlapping two MPGs sensitive to orthogonal polarization states. One of the constituent MPGs is excited when the incident linear polarization state is set to be perpendicular to its slits such that the corresponding surface wave will be reconstructed.

The interference pattern (Supplementary Fig. S4A) between a plane wave and a target surface wave (of the same frequency) resembles the design of single MPG (Supplementary Fig. S4C) since both highlight the places with the same phase value. A surface hologram resulted from the interference can be understood as a 2D analogue to the volume holography. The planar interference pattern can be either recorded by a photoresist layer placed on a metallic film²⁸ or directly transferred into the metallic film by FIB milling²⁹. Certainly, a surface hologram can also be used to reconstruct complex surface waves, e.g. the PABs (Supplementary Fig. S4B). In contrast to the holographic technique, the MPG-enabled metasurfaces as proposed in the paper do not require any interference process, and can be seen as a generalized methodology to satisfy the space-variant momentum matching condition for the reconstruction of a surface wave. Our method can readily be extended to treat a more general case with an oblique illumination (Supplementary Fig. S5). The minor modification to the design process (Fig. 1A) is an additional step that subtracts a linear phase ramp (related to the tilting angle) from the original phase distribution of the target surface wave. The MPGs also result in better reconstruction of surface waves than the holographic method (Supplementar Figs. S6 & S7). Potentially, a direct method like this can be extended to 3D space (e.g. metamaterials) by matching the field distribution in a volume but the realization of required subwavelength features in 3D must be accompanied by technological advancement of 3D nanofabrication, which is still under development. However, the readily available planar nanofabrication technologies such as photolithography, E-beam lithography and FIB ensure that the modular metasurface design concept can be exploited to its maximum capacity for harnessing surface waves. Besides, we also show that our method less sensitive to the variation of dimensions of individual antennas (Supplementary Figs. S8 & S9).

Conclusions

We have demonstrated a straightforward method to reconstruct intricate surface waves based on generalized space-variant momentum matching. This enables the access to the additional degree of freedom in surface optics, e.g. the transverse dimension of SPPs. The mode-matching metasurfaces will also allow one to implement various multiplexing techniques to increase the capacity of plasmonic devices of a given size. In addition, the capability of selectively exciting a specific SPP transverse eigenmode by varying the parameters of the incident coherent radiation paves the way towards a more sophisticated interface for information routing from free-space optics to plasmonic circuits. Our method could also be used in parallel with other existing techniques^{30–32} for coupling light to surface waves.

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Author Contributions

J.L. conceived the design. J.L. and G.Y. prepared the samples. Q.W., L.D. and X.Y. performed the near-field measurements. J.L., W.Q., G.Y. and S.S.K. wrote the main text. All authors reviewed the manuscript.

Additional Information

Supplementary information accompanies this paper at <http://www.nature.com/srep>

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