# Launching Terahertz Surface Wave with Desired Directions

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***Abstract*—Surface wave (SW) has enabled promising applications in various fields. Seeking new approaches in SW control is highly desired in future integrated photonic devices. Controlling SW launching plays an important role in enabling those applications. Here, we develop a versatile platform that allows for manipulating the SW launching by engineering its phase profiles with phase discontinuities using orientation-controlled metallic apertures. Polarization-controllable anomalous SW is experimentally launched and observed in the terahertz frequencies. The proposed approach represents a significant step forward in developing SW-based plasmonic devices.**

## I. Introduction

As an essential form of electromagnetic waves, surface wave (SW) propagates along the metal-dielectric interface and promises unique applications ranging from biological sensing to plasmonic circuitry[1]. However, to realize these applications of SW, SW launching is an essential procedure.

In many cases, manipulating the wavefront of launched SW in a controllable manner can be very important. However, conventional methods usually require either bulk media or complex optical component to shape the SW wavefront, which is impractical for integration into compact miniature SW devices. Meanwhile, the shapes of SW wavefront are in general restricted by specific excitation patterns.

In this work, we apply the recent popular concept of phase discontinuities on SW launching using metasurfaces that consist of orientation-well-designed metallic apertures (SW phase discontinuities)[2,3]. Polarization-controllable directional and focus/diverge SWs are experimentally realized in the terahertz frequencies with solely rectangular-shape excitation patterns under normally incident plane wave.

## II. Results

For an individual narrow aperture, SW can only be excited by the perpendicular polarization component of the incident wave. Considering that an aperture pair[4], as illustrated in Fig. 1, is excited by a normally incident plane wave, at the conditions of circular-polarization incidence $\vec{E}_{in} = \sqrt{2}/2(1, \sigma i)$, aperture distance $s = \lambda_{SW}/2$ and $\theta_2 - \theta_1 = 270°$, the field at point **M** ($|l| \geq s/2$) should be the superposition of the SW fields from the two apertures,

$$\vec{E}_M \propto A e^{ik_{SW}|l|} e^{i2\sigma\theta_1} \hat{a} \tag{1}$$

where $A$ represents the conversion efficiency of an individual aperture from free-space wave to SW; $k_{SW} = 2\pi/\lambda_{SW}$ is the SW wave number with $\lambda_{SW}$ being the SW wavelength; $l$ is the distance between the point **M** and the center of the aperture pair; $\sigma \in \{+,-\}$ represents the left-handed circular polarization (LCP) and right-handed circular polarization (RCP), respectively; $\theta_1$ and $\theta_2$ represent the angles of the normal of the two apertures with respect to the $x$-axis, respectively; and $\hat{a}$ is a unit vector of the SW field.

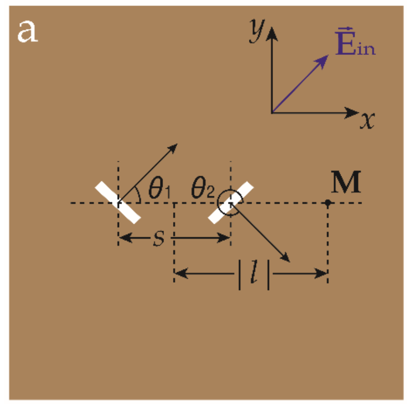


**Fig. 1.** Schematic of a pair of aperture resonators used to deduce the SW launching field at point **M**. The geometric parameters of the two apertures are identical except their rotation angles.

It is seen that the amplitude of the SW field at **M** solely depends on the conversion efficiency, while the phase is freely controllable with a sign determined by the circular-polarization handedness and shift by the orientation angle. This indicates that the aperture pair can be used as a building block to initialize the phase of the launched SW (SW phase discontinuities) to the left and right sides locally ($|l| < s/2$). Also, circular polarization can be used to switch the sign of the phase so as to manipulate the shape of the SW wavefront. More important, the shapes of the SW wavefront will not be restricted by their specific excitation pattern, nearly arbitrary wavefront can be achieved using arbitrary excitation patterns.

Next, we design two kinds of metasurfaces with such aperture pairs for controlling the SW propagation in the terahertz range. Both the patterns of the two metasurfaces are just a straight column shape, one with linear phase profile for controlling terahertz SW direction and the other with parabolic phase profile for controlling terahertz SW focusing. Fig. 2a and d illustrate two sample photos of parts of the metasurfaces with linear and parabolic phase profiles, respectively. The metasurfaces are made from 200 nm aluminum patterning on a 2 mm-thickness quartz substrate using conventional lithography method. The apertures are well designed to resonate at 0.75 THz where SW is mostly excited. In this case, the aperture distance $s$ = 200 μm. The neighboring apertures along the $y$ direction is 120 μm.

Fig. 2b and c illustrate the experimental results of the linear-phase-profile metasurface. As the incident polarization is altered from LCP to RCP, the propagation angle of the launched SW switches its direction from obliquely upwards to obliquely downwards due to the reversed phase gradient. As for the parabolic-phase-profile metasurface, opposite SW wavefront polarity is observed, see Fig. 2e and f. The SW wavefront changes from a focusing shape under LCP incidence to a diverging shape under RCP incidence. The insets in Fig. 2b, c, e and f are the simulated distributions of the real parts of the SW field using commercially available software package *CST Microwave Studio*. The corresponding wavefronts and the flipped behaviors under different circular polarizations show a great agreement with the experiments.

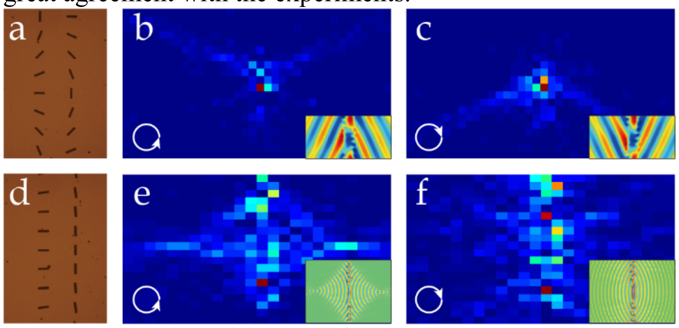


**Fig. 2.** a. Sample photo of the metasurface with linear phase profile. b and c, Experimental field intensity mapping of the launched SW by the linear-phase-profile metasurface under LCP and RCP incidences, respectively. d. Sample photo of the metasurface with parabolic phase profile. e and f, Experimental field intensity mapping of the launched SW by the parabolic-phase-profile metasurface under LCP and RCP incidences, respectively. The insets in b, c, e and f are the corresponding simulated results.

To experimentally obtain the map of the field distribution, a fiber-based near-field terahertz scanning microscope (NTSM) system which allows two dimensional (2D) scan of the SW electric field was applied to map the SW field distributions, as illustrated in Fig. 3. The NTSM working principle is identical to that of the conventional terahertz time-domain spectroscopy, but the terahertz detector is changed to a photoconductive antenna based terahertz near-field probe which allows the detection of terahertz SW. The fiber is used to free the movement of the detection laser beam while the grating pair is used to pre-compensate the dispersion in the fiber so as to prevent the pulse stretch. Here, the circular polarizations were achieved by utilizing a quartz-based terahertz quarter waveplate (@ 0.75 THz). As the setup keeps the time-domain measuring feature, both the amplitude and phase information of the SW field can be obtained simultaneously.

Besides the SW wavefront shaping, the metasurface device

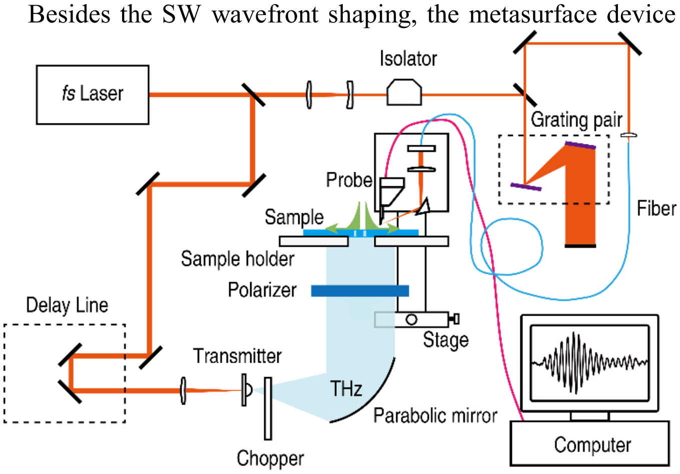


**Fig. 3.** Schematic of the NTSM setup.

has promising applications in polarimetry sensing. This is particularly suitable for designing innovative terahertz components as the time-domain measurement enables acquisition of not only the field amplitude but also the coherent phase information. As an example, the device can be used to detect the polarization state of the incident terahertz wave. SWs excited by an arbitrary incidence polarization are separately launched in two directions. The polarization state can be decoded by extracting the amplitude and phase information of the SWs at both directions representing the LCP and RCP components, respectively, of the incidence polarization. Fig. 4a and b illustrate the experimental and theoretical results of the amplitude distribution and phase difference at two points located in the two directions by adjusting the ellipticity of the incidence polarization at 0.75 THz.

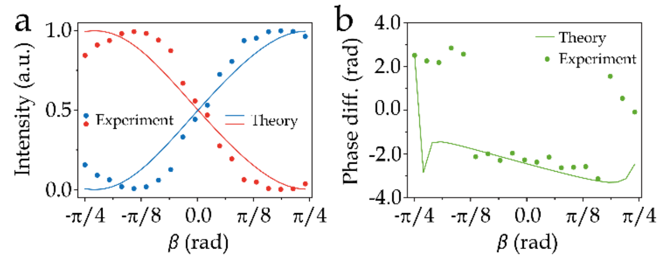


**Fig. 4.** a and b Experimental and theoretical results of normalized intensity distributions a and phase difference b at two points in the two directions as a function of ellipticity of the incidence polarization at 0.75 THz. In the experiment, the ellipticity was smoothly altered by rotating the angle of the quarter-wave plate $\beta$ from $-\pi/4$ (RCP) to $\pi/4$ (LCP).

## III. Summary

In summary, polarization-switchable anomalous SW launching is experimentally demonstrated in a terahertz metasurface platform. Different from the recent SW launching works using free-space phase discontinuities[5,6], our mechanism focuses on the phase discontinuities of SW. The finding illustrates the significance of not only the phase control in SW launching, but also the near-field microscopy in understanding of the interactions between electromagnetic wave and subwavelength structures. Besides, we also find that this unique approach would enable promising applications in polarimetry and refractive index sensing. The proposed mechanism in the terahertz frequencies could also be expanded to the other bands of the broad electromagnetic spectra.

## References

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