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Vortex excites unidirectional water waves near ancient Luoyang Bridge

Yichen Li, Xinhua Hu†

Department of Materials Science and Key Laboratory of Micro- and Nano-Photonic Structures (Ministry of Education), Fudan University, Shanghai 200433, China
Corresponding author. E-mail: †huxh@fudan.edu.cn
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Since the discovery of generalized Snell's law in 2011 [1], metasurfaces have opened up the mainstream of arbitrary wavefront manipulation in electromagnetism. Using a gradient-index metasurface, the parallel wavenumber k_x of reflected wave can be not equal to the incident one ($k_x = \xi + k_0 \sin\theta_i$, where k_0 and θ_i are the incident wavenumber and angle, and ξ is the phase gradient of metasurface in its supercell) [1]. When $\xi > k_0$, the reflected wave becomes a surface wave bounded on the metasurface (where $|k_x| > k_0$, k_z is imaginary, and z is normal to the metasurface) [2]. However, as research of metasurfaces continually evolves, some articles have pointed out that such graded metasurfaces suffer from a series of problems [3–6]. In particular, multiple metallic resonators are adopted in a subwavelength supercell, resulting in impedance mismatch, moderate conversion efficiency, wave absorption, and fabrication complexity. Hence, although the approach of graded metasurfaces has been demonstrated in the microwave regime, it is hard to extend to infrared and optical ranges with shorter wavelengths. To solve this problem, Ra'di *et al.* [7] devised metagratings with periodic arrays of bianisotropic scatterers and showed that they enable wave front engineering with unitary efficiency and significantly lower fabrication demands.

In addition to improving efficiency, quantum information transfer [8–10] and nano-optical metrology [11] require the manipulation of directional surface plasmon polaritons (SPPs) in plasmonic circuits. In 2013, Rodríguez-Fortuño *et al.* [8] employed polarized dipoles at the interface of metal to excite unidirectional SPPs. The y-direction magnetic field H_y for circularly polarized dipole $\boldsymbol{p}_{2\mathrm{D}} = [p_x,\ p_z]$ is written as $H_y(x,z) = \int H_y(k_x,z)\,\mathrm{e}^{\mathrm{i}k_x x}\mathrm{d}k_x$, where

$$H_y\left(k_x, z\right) = \frac{\mathrm{i}\omega}{8\pi^2}\left(p_z\frac{k_x}{k_z} \mp p_x\right)\mathrm{e}^{\mathrm{i}k_z|z-z_{\mathrm{dipole}}|}. \tag{1}$$

$\omega = ck_0$ is angular frequency, c is the speed of light in vacuum, and minus (plus) sign applies to $z > z_{\mathrm{dipole}}$ ($z < z_{\mathrm{dipole}}$) in Eq. (1) with z_{dipole} being the z-direction coordinate of the dipole. Along z-direction, H_y with $|k_x| < k_0$ ($|k_x| > k_0$) is a propagating wave (evanescent wave). When there is a right-hand elliptical polarized dipole $\boldsymbol{p}_{2\mathrm{D}} = [1, -0.705\mathrm{i}]$ at $d = 0.3\lambda$ (λ is the vacuum wavelength) above the infinitely thick metal, surface waves with different k_x in $k_x < -k_0$ ($k_x > k_0$) direction undergo constructive (destructive) interference, which results in only left propagation of surface SPPs at metal surface. Experimentally, SPPs are excited mainly on the left (right) side of the slit by right-handed (left-handed) circularly-polarized light grazing the slit gratings (see Fig. S2 in Ref. [8]). Other important methods of generating asymmetric SPPs, such as polarized incident light controlling SPPs direction on the metasurface [9, 10], shifted (1,0)-mode Hermite– Gaussian beams illuminating a pair of slot antennas [11], are also found.

The marvelous physics of water waves, as one of the most common forms of fluctuations, has been intensively studied for decades [12, 13]. The wave equations of water waves and electromagnetic waves share similar forms [12–15]. However, contrast to unidirectional SPPs, manipulating unidirectional-propagation water waves have not been discovered until 2022. Han *et al.* [14] designed a non-resonant groove grating for water waves. In simulations (water depth $h = 0.3\lambda$), there is a vortex source 0.2λ away from the grating and thus the vertical displacement of water surface can be written as $\eta(x,y) = \int \tilde{\eta}(k_x,y)\mathrm{e}^{\mathrm{i}k_x x}\mathrm{d}k_x$ with

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$$\tilde{\eta}\left(k_x, y\right) = \frac{1}{\pi k_0}\left(a_z \frac{k_x}{k_y} \mp a_x\right) \mathrm{e}^{\mathrm{i}k_y\left|y - y_{\mathrm{source}}\right|}. \quad (2)$$

Wavenumber $k_0 = 2\pi/\lambda$, k_x and k_y are the wavenumbers in the x and y directions, and the polarizability of the source $\boldsymbol{P} = [a_x,\ a_z]$. In Eq. (2), the minus (plus) sign corresponds to $y > y_{\mathrm{source}}$ ($y < y_{\mathrm{source}}$) with y_{source} being the y-coordinate of the vortex source. The vortex source with right-hand circular polarization $\boldsymbol{P} = [1, -\mathrm{i}]$ generates unidirectional water waves bound to the groove grating (period $d = \lambda/5.5$, groove width $a = \lambda/11$), called as "water wave polaritons" (namely like SPPs). In the qualitative experiments ($h = 1.5$ cm), a screw propeller served as a vortex source ($\lambda = 5$ cm) with floating balls on its left and right sides. When the clockwise (counter-clockwise) propeller is about 0.2λ away from the polylactic acid (PLA) groove grating, the unidirectional 'water wave polaritons' drive the balls on the right (left) to move rapidly, while the balls on the left (right) are basically stationary.

Two years later, in a recent work [15], Han *et al.* further investigated the unidirectional propagation properties of "water wave excitations" near metagratings. The authors were inspired by an ancient bridge in China, the Luoyang Bridge [16] with an array of 46 boat-shaped pillars, and designed the metagrating into a similar shape. The ancient Luoyang Bridge is more than 1000 years old, located in Quanzhou, China. They discovered a fantastic physical feature of the ancient bridge: A vortex source excites unidirectional water waves bound to the Luoyang Bridge.

In simulations ($h = 3$ m), the source ($y_{\mathrm{source}} = 6$ m) is similar to Eq. (2) [8], but with left-handed circular polarization $\boldsymbol{P} = [1, \mathrm{i}]$, and the Luoyang Bridge model is along $y = 0$. The surface waves generated by the source ($\lambda = 46.4$ m) near the model are greatly enhanced (attenuated) on the left (right) side of the source with a good unidirectional propagating property. Theoretically, they provide layered equivalent medium method to analyze water waves near the Luoyang Bridge model: The $\overset{\leftrightarrow}{u}$ and g of the rectangular parts of the model are $u_x = 0$, $u_y = a/(d{\cdot}u_0)$, $g = d/(a{\cdot}g_0)$ [17], where g_0 is gravitational acceleration without metamaterials. The isosceles triangle parts of the model are seen as many rectangles with infinitesimal thickness and linearly scaled width, which $\overset{\leftrightarrow}{u}$ and g change linearly. They further obtain dispersion relation of the equivalent anisotropic water layer from anisotropic transmission matrix. The equivalent water layer and the perfectly matched layer are spliced on both sides of the Luoyang bridge model to simulate an infinitely long metagrating. The numerical field patterns show that the anisotropic water layer agrees well with the Luoyang bridge model.

In the qualitative experiment, when the screw propeller, as a wave source ($\lambda = 4.64$ m), rotates in counterclockwise (clockwise) direction, the wave amplitude is weakened to the right (left) of the wave source, and the unidirectional surface waves propagating to the left (right) near PLA Luoyang model are enhanced. Furthermore, they used a ship instead of a screw propeller as a clockwise rotating vortex source (about $\lambda = 46.4$ m) near the real Luoyang Bridge (about $h = 3$ m). To emphasize the results, they placed two strings of floating balls on both sides of the wave source. The ball string on the left (right) side produces a larger (smaller) displacement, consistent with theoretical and laboratory results.

We believe such exotic phenomenon of vortex to unidirectional surface wave conversion provides a good idea for utilizing the huge and renewable ocean's energy [18]. In reality, giant vortex machinery, powered by electricity converted from stored ocean energy, excite intensive and unidirectional surface waves near metagratings, which potentially has much environmental and commercial value for marine garbage removal and transportation of marine cargo. Also, their group has previously found that the ancient Luoyang Bridge can reduce the energy of transmitted water waves to protect itself from overwhelming erosion for 1000 years [19], which reflects the great wisdom of the ancient people. In future, the nonlinear effect deserves further consideration due to the inherent complexity in ocean water waves. Similar to manipulating unidirectional SPPs, further improving the unidirectionality of the water waves and the conversion efficiency still need to be further studied.

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