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ABSTRACT

In developing strategies for manipulating surface electromagnetic waves, it has been recently recognized that a complete forbidden bandgap can exist in a periodic surface-wave photonic crystal, which has subsequently produced various surface-wave photonic devices. However, it is not obvious whether such a concept can be extended to a quasi-periodic surface-wave system that lacks translational symmetry. Here, we experimentally demonstrate that a surface-wave photonic quasicrystal that lacks short-range order can also exhibit a forbidden bandgap for surface electromagnetic waves. The lower cutoff of this forbidden bandgap is mainly determined by the maximum separation between the nearest neighboring pillars. Point defects within this bandgap show distinct properties compared to a periodic photonic crystal in the absence of translational symmetry. A line-defect waveguide, which is crafted out of this surface-wave photonic quasicrystal by shortening a random row of metallic rods, is also demonstrated to guide and bend surface waves around sharp corners along an irregular waveguiding path.

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Photonic crystals (PCs), periodic systems with forbidden bandgaps for electromagnetic (EM) waves in all directions,¹ have attracted great interest in the past few decades due to their appealing scientific and engineering applications. However, because PCs are based on Bragg interferences, PC devices are generally limited to the wavelength scale. On the other hand, surface EM waves at the metal/dielectric interfaces [“surface plasmons” (SPs) at optical frequencies]^{2,3} offer the potential for controlling light on a subwavelength scale because of their intrinsic subwavelength nature. Although SPs in the visible/near-infrared spectra suffer from severe metallic loss, spoof SPs^{4–15} or the surface EM waves at frequencies ranging from microwave, terahertz to far-infrared hold promising application prospects because of their outstanding waveguiding performance with negligible loss. Recently, by merging the subwavelength feature of spoof SPs with the forbidden bandgap of PCs, some unconventional surface-wave functionalities and devices based on surface-wave PCs^{16–18} are developed, such as multi-directional splitting of surface waves with full bandwidth isolation,¹⁹ efficient broadband guiding and bending of surface waves along a line-defect waveguide,²⁰ and ultra-slow-wave devices.²¹

While all the previous surface-wave devices utilizing the photonic bandgap were demonstrated in periodic surface-wave PCs,^{16–21}

whether a similar bandgap can exist in a surface-wave quasicrystal system that exhibits long-range periodicity still remains unknown. Surface-wave PCs are unique in the sense that they combine the properties of conventional periodic PCs¹ and spoof SPs.^{4–15} In a conventional PC, the interaction between a unit cell and its surrounding periodic unit cells (e.g., the interaction between a rod and its surrounding rods) forms Bragg scattering, which is the very origin of the bandgap. However, in surface-wave PCs, the forbidden bandgap originates from both the local resonance of each unit cells and their interactions with surrounding unit cells. In fact, even without the surrounding surface-wave bandgap crystal, one single row of metallic pillars themselves can also guide surface waves. This is a typical traditional spoof SP waveguide (widely referred to as “domino plasmons”⁸) that has been studied extensively with various device applications.^{9–11} The local resonance of each unit cell provides the vertical confinement and guiding of surface waves on the structured metal surface, which cannot be achieved in conventional PCs.

Surface-wave PCs also exhibit unique properties that are different from those of metamaterials. Owing to the deep-subwavelength periodicity of metamaterials, it can be theoretically modeled by effective medium theory. However, PCs, whose periodicity is comparable with

the operating wavelength, cannot be modeled by effective medium theory but Brillouin zones and Bloch theorem. In the [supplementary material](#), using the simulated band structure and measured near-field transmission spectrum, we have experimentally demonstrated that the square array of metallic pillars standing on a flat metal surface is a new type of surface-wave photonic crystal, rather than metamaterials. In particular, surface-wave PCs are similar to a new type of optical media-photonic hypercrystals,²² that possess the properties of both the photonic bandgap of photonic crystals and the subwavelength nature of SPs at the metal-dielectric interface.

In a locally resonant wire-medium metamaterial,¹⁷ the resonance frequency and forbidden bandgap are fully determined by a single wire itself, with almost zero influence from the surrounding wires. In this case, the wires can be even randomly placed without affecting the resonance frequencies and the forbidden bandgap.²³ Being different from a conventional PC and a locally resonant wire-medium metamaterial, in a surface-wave PC, a unit cell exhibits both local resonance and near-field interaction with its neighboring unit cells. Therefore, the resonance frequency and forbidden bandgap of surface-wave PCs are determined by both a single unit cell itself and the surrounding unit cells. It is, thus, worthwhile to verify if the periodicity is the necessary condition of a bandgap for manipulating surface wave propagation. Note that the optical interference properties of a number of photonic quasicrystals in various optics areas have been demonstrated. Examples include wave propagation in photonic quasicrystals^{24–28} and extraordinary transmission through plasmonic quasicrystals.^{29,30} However, photonic quasicrystals for the propagation of surface waves have not been reported.

Inspired by a photonic quasicrystal^{24–28} whose crystal lattice lacks the translational symmetry, here, we experimentally demonstrate that a surface-wave photonic quasicrystal with Penrose tiling²⁹ also possesses a complete bandgap for surface EM waves. The absence of the translational symmetry in the Penrose lattice allows different resonance frequencies and localization properties of defect cavity resonance modes at different defect positions. Moreover, efficient guiding and bending of surface waves along a line-defect waveguide by shortening a random row of metallic rods in this surface-wave photonic quasicrystal are also demonstrated with transmission spectra measured and mode profiles imaged directly.

We first consider an array of circular aluminum rods with a radius of $r = 1.25$ mm and a height of $h = 5$ mm on a flat aluminum plate, as shown in Fig. 1(a), where each rod is located at a vertex of the two-dimensional (2D) Penrose lattice. The edge of each rhomb is $d = 5$ mm. The Penrose lattice utilizes two different types of tiles to fill the whole 2D plane: a thin rhomb with vertex angles of 36° and 144° and a fat rhomb with vertex angles of 72° and 108° , as shown in the inset of Fig. 1(a). The Penrose lattice is a type of photonic quasicrystal that exhibits long-range order but lacks translation symmetry (short-range order). Thus, these structures, which lie between periodic (with both long-range and short-range order) and disordered (without long-range and short-range order) structures, exclude the possibility of describing them using well-established analytical tools (such as the Brillouin zone and Bloch theory) that are unique to periodic lattices. In this situation, numerical simulations^{24–28} and experimental measurements²⁹ are the principle methods to explore the properties of photonic quasicrystals.

To experimentally demonstrate the existence of a bandgap in the surface-wave photonic quasicrystal, we measured the transmission

FIG. 1. (a) Photo of a 2D Penrose-type surface-wave photonic quasicrystal with aluminum rods (radius $r = 1.25$ mm; height $h = 5$ mm) placed at the vertices of thin and fat rhomb tiles on a flat aluminum plate. The length of the rhomb side is $d = 5$ mm. (b) Measured transmission spectrum (S-parameter S_{21}) of the surface-wave photonic quasicrystal. (c) Photo of the traditional periodic surface-wave PCs that consist of a square array of circular aluminum rods with a radius of $r = 1.25$ mm a height of $h = 5$ mm, and a periodicity of $d = 5$ mm. (d) Measured transmission spectrum (S-parameter S_{21}) of the periodic surface-wave PCs.

spectrum of surface waves supported on this quasicrystal structure at microwave frequencies. Two homemade monopole antennas (with dimensions of 1.5 mm in diameter and 5 mm in length), connected to a vector network analyzer (VNA) R&S ZVL-13, were used as the source and the probe placed at opposite sides of the surface-wave photonic quasicrystal to measure the transmission coefficient (S-parameters S_{21}) of surface waves. Note that because of the impedance mismatch, the monopole antennas are inefficient and mainly sensitive to the evanescent waves. The measured transmission coefficient should be understood as a relative transmission measurement. The size of the examined samples is 80×80 mm² and is large enough to detect the forbidden bandgap of the surface-wave photonic quasicrystal. Figure 1(b) shows the measured transmission coefficient between the source and the probe, from which we can clearly observe a forbidden bandgap starting from 12.6 GHz (the upper edge of the bandgap is not shown because of the frequency range limit of VNA), within which the relative transmission from -40 dB to -35 dB is at the noise level. For comparison, we then measured the transmission coefficient of a previous periodic surface-wave PC,^{18–20} as shown in Fig. 1(c), with a periodicity of $d = 5$ mm. The measured transmission spectrum of the periodic surface-wave PC is presented in Fig. 1(d), which also exhibits a wide forbidden bandgap starting from 12.6 GHz.²⁰ Evidently, almost the same photonic bandgap exists for both periodic surface-wave PCs and non-periodic surface-wave photonic quasicrystals, indicating that short-range periodicity is not a necessary condition of the forbidden bandgap for surface EM waves.

To construct a defect cavity in the surface-wave photonic quasicrystal, we replace one metallic rod with a slightly shorter one.¹⁸ Due to the absence of translational symmetry, the properties (resonance frequency, localization, and field pattern) of the defect cavity can be very different from those in a periodic surface-wave PC.¹⁸ We first slightly shorten a metallic rod from $h = 5$ mm to $h_d = 4.3$ mm at the center of the surface-wave photonic quasicrystal [labeled as A in Fig. 2(a)]. This defect cavity is symmetrically surrounded by five nearest

FIG. 2. (a) Schematic figure showing the quasicrystal (Penrose lattice) arrangement of aluminum rods (red dots) on a flat aluminum surface. Three defects (white dots) labeled as A, B, and C are induced by shortening a metallic rod from $h = 5$ mm to $h_d = 4.3$ mm at each site. (b) Measured near-field response spectra of a surface-wave photonic quasicrystal with a single point defect (A: red line, B: green line, and C: blue line), without any defect (black line) and when the pillar is removed (gray line). (c) Observed field pattern (E_z) of defect cavity A at the resonance frequency of 13.75 GHz. (d) Observed field pattern (E_z) of defect cavity B at the resonance frequency of 14.21 GHz. (e) Observed field pattern (E_z) of defect cavity C at the resonance frequency of 14.52 GHz.

neighboring metallic rods. With the source placed in the defect cavity and the probe placed above the defect cavity, the measured near-field response spectrum of this surface defect cavity [red line in Fig. 2(b)] reveals a resonance mode at a frequency of $f_A = 13.75$ GHz located within the forbidden bandgap of the surrounding surface-wave photonic quasicrystal (purple region). For comparison, by maintaining the positions of the source and probe, we also measured the near-field response spectrum of the perfect surface-wave photonic quasicrystal without any defect [black line in Fig. 2(b)]. No resonance peak can be observed. To further verify that the resonance of the defect cavity is due to the local resonance of the shortened pillar rather than the backward scattering from the non-periodic environment, we completely removed metallic rod A and measured the near-field response spectrum, as shown in Fig. 2(b) (gray line), and no resonance peaks emerge. Thus, we make sure that the surface defect states are created due to the local resonance of the shortened metallic rod. We also imaged the near-field profile (E_z) of the surface defect resonance mode using a microwave near-field scanning system, as shown in Fig. 2(c). The fivefold rotational symmetry is clearly observed. This further confirms that a surface defect cavity mode is created at the defect site.

If we shorten a metallic rod at another position [labeled as B in Fig. 2(a)] from $h = 5$ mm to $h_d = 4.3$ mm, the measured near-field response spectrum [green line in Fig. 2(b)] and near-field distribution [Fig. 2(d)] are quite different from those of the defect state at site A due to the change in the surrounding environment of the shortened rod. We now shorten a metallic rod at the third position [labeled as C in Fig. 2(a)] from $h = 5$ mm to $h_d = 4.3$ mm. This results in another

different defect state whose measured near-field response spectrum and near-field distribution are presented in Fig. 2(b) (blue line) and Fig. 2(e), respectively. We note that shortening the metallic rod at site A corresponds to a defect cavity state with lower resonance frequency ($f_A = 13.75$ GHz), while shortening metallic rods at sites B and C corresponds to higher resonance frequencies ($f_B = 14.21$ GHz and $f_C = 14.52$ GHz). This is because at site A, the five nearest neighboring rods are placed around the defect rod with an equal distance. At site B, however, one nearest neighboring rod has been closer to the defect rod than other surrounding rods, producing a higher resonance frequency. At site C, two nearest neighboring rods are closer to the defect rod, giving rise to an even higher resonance frequency.

Using the same experimental setup, we now move on to construct more complex functionalities in surface-wave photonic quasicrystals: a quasi-straight line-defect waveguide and a line-defect waveguide with a sharp corner. We first construct a quasi-straight line-defect waveguide by shorting a row of aluminum rods from $h = 5$ mm to $h_d = 4.3$ mm, as shown in the inset of Fig. 3(a). Then, we measured the relative transmission coefficient of the waveguide, as shown in Fig. 3(a) (red line). Compared to the transmission spectrum of a perfect surface-wave photonic quasicrystal without the line-defect [black line in Fig. 3(a)], we can clearly observe a waveguiding band within the bandgap of the surrounding surface-wave photonic quasicrystal (purple region) starting from 12.6 GHz. The measured spatial distribution of the E_z component in a transverse xy -plane 2 mm above the waveguide is presented in Fig. 3(b), which shows that surface waves efficiently propagate along the waveguide. From the measured near-field distribution (including phase information) of the quasi-straight line-defect waveguide shown in Fig. 3(b), we can approximately evaluate that the effective wavelength of the surface waves is about $\lambda_{spp} = 3d$, where d is the edge of each rhomb that consists of the quasicrystal. For comparison, by removing all surrounding un-shortened rods, we also measured the transmission spectrum through only the defect rods (blue line), which works as a quasi-straight domino plasmon waveguide.⁸ Because of the absence of surrounding rods, the surface-wave propagation is not affected by the bandgap boundary at 12.6 GHz. The cutoff at around 14 GHz is an intrinsic polaritonic property of the domino plasmons.

We then demonstrate a line-defect waveguide with a sharp corner. As shown in the inset of Fig. 4(a), a sharp corner in the surface-wave photonic quasicrystal can be created by shortening a row

FIG. 3. (a) Measured transmission spectra of a quasi-straight line-defect waveguide (red line) and a perfect surface-wave photonic quasicrystal without the line-defect (black line) as well as a quasi-straight domino plasmon waveguide (blue line) after removal. (b) Measured spatial distribution of the E_z component in a transverse xy -plane 2 mm above the waveguide at 13.5 GHz, showing the source and probe locations.

FIG. 4. (a) Measured transmission spectra of a bent line-defect waveguide (pink line) and a perfect surface-wave photonic quasicrystal without any defect (black line), as well as a bent domino plasmon waveguide with a sharp corner (blue line) after removing surrounding un-shortened pillars. The inset shows the line-defect waveguide configuration. (b) Observed field pattern (E_z) above the sharp corner at 13.5 GHz. Two monopole antennas as the source and probe are indicated with a pair of black arrows.

of aluminum rods in x and y directions successively. The measured transmission spectrum of the sharp corner is shown in Fig. 4(a) (pink line), and a transmission band is observed within the forbidden bandgap of the surrounding surface-wave photonic quasicrystal, which is similar to that of the quasi-straight line-defect waveguide presented in Fig. 3(a). For comparison, the transmission through the perfect surface-wave photonic quasicrystal is also plotted in Fig. 4(a) (black line), which shows low transmission values. As presented in Fig. 4(b), the measured electric field distribution in a transverse xy -plane 2 mm above the sharp corner shows clearly that surface waves can be efficiently transmitted through a sharp corner in a surface-wave photonic quasicrystal, which is similar to the wave bending phenomena in a periodic surface-wave PC.²⁰ In contrast, when all surrounding rods are removed, the transmission through the sharp corner greatly drops, as presented in Fig. 4(a) (blue line).

In conclusion, we have experimentally demonstrated that a photonic bandgap can exist in a surface-wave photonic quasicrystal that is composed of the Penrose tiling of aluminum pillars on a flat metal surface. This shows that short-range periodicity is not a necessary condition for the existence of the surface-wave photonic bandgap. The cutoff frequencies of both the periodic and non-periodic surface-wave PCs are determined by the maximum separation between the nearest neighboring metallic pillars. Moreover, efficient guiding and bending of surface waves in surface-wave photonic quasicrystals are also demonstrated.

See the [supplementary material](#) for the experimental demonstration of the surface-wave photonic bandgap of a periodic surface-wave photonic crystal.

AUTHORS' CONTRIBUTIONS

Y.A. and Z.G. contributed equally to this work.

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