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Guiding, bending, and splitting of coupled defect surface modes in a surface-wave photonic crystal

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We experimentally demonstrate a type of waveguiding mechanism for coupled surface-wave defect modes in a surface-wave photonic crystal. Unlike conventional spoof surface plasmon waveguides, waveguiding of coupled surface-wave defect modes is achieved through weak coupling between tightly localized defect cavities in an otherwise gapped surface-wave photonic crystal, as a classical wave analogue of tight-binding electronic wavefunctions in solid state lattices. Wave patterns associated with the high transmission of coupled defect surface modes are directly mapped with a near-field microwave scanning probe for various structures including a straight waveguide, a sharp corner, and a T-shaped splitter. These results may find use in the design of integrated surface-wave devices with suppressed crosstalk. © 2016 AIP Publishing LLC.

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Photonic crystals, also known as photonic bandgap (PBG) materials, are artificial periodic dielectric or metallic structures which can forbid the propagation of electromagnetic (EM) waves in a certain frequency range in all directions.^{1–3} By locally breaking the translational symmetry of photonic crystals, highly localized point defect modes within the photonic bandgap can be created, being analogous to the localized impurity states in a semiconductor.⁴ Thus, only evanescent waves can penetrate, from this defect location into the gapped photonic crystal within a finite distance, opening the opportunity for photons to hop from one defect cavity to the neighboring one. Following this concept, waveguiding along the impurity chains in photonic insulators⁵ and through coupled defect modes⁶ are theoretically investigated and experimentally verified^{7–9} in the context of photonic crystals. However, because photonic crystals work with Bragg interference, the mode profile of these defect modes are generally diffraction-limited, i.e., being limited to the scale of about half a wavelength.

On the other hand, electromagnetic modes supported on periodically textured metal surfaces, which are commonly termed as spoof (or designer) surface plasmons,^{10–22} possess spatial scales typically much smaller than the wavelength. In particular, some structured metal surfaces exhibit a complete photonic bandgap where no surface guided modes are permitted.^{23–26} Recently, by introducing an engineered defect on a perfectly structured metal surface, a tightly localized subwavelength surface defect mode that emerges in the photonic bandgap is proposed theoretically^{27,28} and verified experimentally²⁹ in the microwave regime.

Here, we demonstrate that it is possible to merge the subwavelength feature of spoof surface plasmons with the waveguiding mechanism of coupled defect modes in the

context of photonic crystals. This can provide an alternative way to manipulate the propagation of surface waves at sub-wavelength scales on structured metal surfaces. Compared with conventional waveguides of spoof surface plasmons,^{10–22} which generally suffer from scattering and crosstalk when packed densely, this coupled-defect surface waveguide (CDSW) is achieved through weak coupling between otherwise tightly localized surface defect cavities, which allows shaping the flow of surface waves almost as well³⁰ with minimal crosstalk.

We start our demonstration with a perfectly structured metal surface as an ideal surface-wave photonic crystal, as shown in Fig. 1(a). This surface-wave photonic crystal consists of a square array (25×25) of cylindrical aluminum pillars with radius $r = 1.25$ mm, height $h = 5$ mm, and period $d = 5$ mm. By performing three-dimensional (3D) Finite Integration Technique (FIT) eigenmode simulations, we can obtain the band structure of the corresponding infinite surface-wave photonic crystal, which reveals a surface-wave bandgap from 12.6 GHz to 27 GHz, as shown in Fig. 1(b).

Our goal is to use this structured metal surface to control the propagation of surface waves through coupled surface defect cavities. We start by designing the most basic component: a surface defect cavity. For this purpose, we partially reduce the height of one pillar at the center from $h = 5$ mm to $h_d = 4.15$ mm, while keeping the rest of the pillars unchanged, as indicated by a blank dot at the center of the inset in Fig. 2(b). Thus, the resonance frequency of the shortened pillar falls within the bandgap of surface-wave photonic crystal, and a defect state can be expected near the shortened pillar. To experimentally demonstrate this surface defect cavity, we employ a near-field scanning system working in the microwave regime. The experimental setup consists of a vector network analyzer (R&S ZVL-13) and a pair of home-made electrically short monopole antennas placed in the near-field of the metal surface to excite and probe the surface

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FIG. 1. (a) Photography of the surface-wave photonic crystal that consists of a square array of cylindrical pillars with radius $r = 1.25$ mm, height $h = 5$ mm, and periodicity $d = 5$ mm. (b) Projected photonic band structure of propagating surface modes. Radiation modes (shaded regions) above the light cone are not displayed.

waves, as shown in the inset of Fig. 2(a). The monopole source and probe are arranged in the direction normal to the sample surface and mainly sensitive to the vertical component of electric field (E_z). The probe antenna is mounted on a xy -motorized stage to measure the transmission between the two ports (widely called “S-parameter S_{21} ”) at any given position.

We then test this surface defect cavity. We first measure the transmission S_{21} in the full surface-wave photonic crystal without any defect by placing the monopole source at the boundary of the surface-wave photonic crystal and the probe 1 mm above one chosen pillar, as shown in the inset of Fig. 2(a). Below the cutoff frequency of 12.6 GHz, we can see some weak resonant peaks in the transmission spectrum [black line in Fig. 2(a)], which means that some surface modes can be supported on this surface-wave photonic

crystal. Then, we replace the chosen pillar by a shorter one with height $h_d = 4.15$ mm and keep other parts of the experimental setup unchanged. We plot the transmission in the presence of the single surface defect cavity in Fig. 2(a) with a red curve. Evidently, except for the weak resonant peaks below the cutoff frequency of 12.6 GHz, an ultra-strong resonant peak appears in the bandgap of the surface-wave photonic crystal, which corresponds to the defect cavity created on the textured metal surface. Of equal interest is the spatial extension of the surface cavity mode created by the defect. Using the microwave near-field scanning stage, we measure the spatial distribution of the electric field (E_z) around the defect cavity at its resonant frequency 13.5 GHz, as shown in Fig. 2(b). It is clear that a highly localized spoof surface plasmon cavity mode is formed on the structured metal surface. For comparison, the electric field distribution of the defect cavity mode on a transverse xy -plane 1 mm above the textured metal surface obtained by FIT simulation is shown in Fig. 2(c). The agreement between the experiment and simulation results is evident. We also present the simulated E_z field distribution in the vertical central xz -plane of the single cavity, as shown in the inset of Fig. 2(d), which further confirms that the surface defect cavity modes are highly confined in the defect site and decay exponentially in both horizontal and vertical directions.

We now move on to more complex components for guiding surface waves. We first construct a straight waveguide by shortening a row of metallic pillars alternately, as shown in the inset of Fig. 3(a). The dispersion relation of the surface-wave defect modes can be obtained by applying the Floquet-Bloch theorem and using a commercial finite-integration time-domain algorithm, as plotted in Fig. 3(a). Here, even though the surface waves are guided by metallic pillars similar to the case of spoof surface plasmons supported by a square array of metallic pillars,^{25,29,31} the dispersion relation is very different from that of conventional spoof surface plasmons, which starts at the light line and tends to zero group velocity at the band edge. Indeed, when excited, the cavity modes of each surface defect are tightly confined at the defect site and only a small portion of the field penetrates in the form of evanescent waves to reach the

FIG. 2. (a) Measured near-field transmission spectra of a surface-wave photonic crystal with a single point defect (red line) and without any defect (black line). Inset shows the experimental setup. (b) Observed field pattern (E_z) when the source is inside the point defect at the resonance frequency of 13.5 GHz. Inset shows the structured metallic surface with a point defect at the center. (c) Simulated field pattern (E_z) in the xy plane when the source is inside the point defect at the resonance frequency of 13.5 GHz. (d) Simulated field pattern (E_z) in the vertical xz plane (black dashed line in Fig. 2(c)) when the source is inside the point defect at the resonance frequency of 13.5 GHz.

FIG. 3. (a) Simulated dispersion relation of the waveguiding band for the coupled defect surface waveguide. Inset illustrates the waveguide configuration. (b) Measured normalized transmission spectrum for a straight coupled defect surface waveguide (red line) and an ideal surface-wave photonic crystal without any defect (black line). (c) Measured field pattern (E_z) of a straight coupled defect surface waveguide at 13.5 GHz. (d) Simulated field pattern (E_z) of a straight coupled defect surface waveguide at 13.5 GHz.

nearest neighbor. Thus, surface waves can propagate via hopping due to the weak coupling between neighboring cavities. This nearest-neighbor coupling is exactly the classic wave analogue of tight-binding (TB) limit in solid state physics.³² Hence, similar to coupled defect modes in photonic crystals⁷ and coupled resonator optical waveguide (CROW),⁶ the dispersion relation of CDSW exhibits a shape of sine function centered at the resonance frequency of a single surface defect cavity, as shown in Fig. 3(a), rather than a polaritonic dispersion relation.

We then construct and measure the normalized transmission spectrum through a straight CDSW with 12 unit cells, as shown in Fig. 3(b). We observe, within the photonic bandgap, a waveguiding band extending from 13.35 GHz to 13.65 GHz, with a normalized transmission of 80% and a band width of $\Delta\omega = 0.3$ GHz. We also plot the normalized transmission spectrum of the full surface-wave photonic crystal for comparison, which shows a wide forbidden band that starts from 12.6 GHz, being consistent with the band structure shown in Fig. 1(b). Measured and simulated maps of the spatial distributions of electric field 1 mm above the sample are presented in Figs. 3(c) and 3(d), respectively. Evidently, surface waves hop from one cavity to another, forming a very efficient and subwavelength confined propagation. In experiment, we observed the deterioration of guided waves [Fig. 3(c)] along the propagation direction, which mainly comes from the fabrication imperfections and metallic loss. We adopt the following way to estimate the propagation length l of guided waves. We first measure the transmission decay over 11 periods in a straight CDSW. Then, the imaginary part of the propagation wavevector $Im(k)$ can be extracted from the measurement. Finally, the mode propagation length can be obtained as $l = [2Im(k)]^{-1}$. In the experiment, we fixed the frequency at 13.5 GHz [the center

of the normalized transmission spectrum in Fig. 3(b)] and the whole straight waveguide length is 11 d (110 mm) with 80% transmission. Thus, we can deduce the propagation length of CDSW at 13.5 GHz ($\lambda = 22.2$ mm) is about 11.2λ .

Since the propagation of surface waves in the proposed CDSW stems from the resonant nature of the defect cavity, we can tailor unit cells locally to shape the flow of surface waves along a prescribed path. We take the bending of surface waves through a sharp corner [inset of Fig. 4(a)] as an example. The measured normalized transmission spectrum through this sharp corner is shown in Fig. 4(a). A waveguiding band extending from 13.35 GHz to 13.65 GHz is observed, whose frequency range and normalized transmission are almost the same with the straight waveguide. The measured and simulated electric field distributions in a transverse xy -plane 1 mm above the metal surface are presented in Figs. 4(b) and 4(c), respectively. To further confirm that high transmission through multiple sharp bends is possible, we simulate a 180° CDSW which consists of two sharp corners and present the E_z field distribution at 13.5 GHz in a transverse xy -plane 1 mm above the metal surface, as shown in Fig. 4(d). Evidently, the high transmission of surface waves does not depend on the number of sharp corners.

This waveguiding mechanism is in contrast with that of conventional spoof surface plasmons waveguides in which backscattering and radiation can seriously impair their capability of bending surface waves with a small bending radius. The high transmission of CDSW through a right-angle sharp corner is achieved mainly for two reasons. First, according to Yariv's theory of coupled-resonator optical waveguide (CROW),⁶ if the couplings between the resonator at the corner and its two nearest neighbors on the two waveguide arms are the same, the transmission through the sharp corner can be

FIG. 4. (a) Measured normalized transmission spectrum of a 90° sharp corner. Inset shows the sharp corner geometry, where input/output ports are indicated with red arrows. (b) Observed field pattern (E_z) of a sharp corner at 13.5 GHz. Monopole source and probe are indicated with a pair of red arrows. (c) Simulated field pattern (E_z) of a sharp corner at 13.5 GHz. (d) Simulated field pattern (E_z) of a 180° bend which consists of two sharp corners.

theoretically perfect. In our case, despite the presence of loss, the near-field couplings between the defect at the corner and its two nearest neighbors are almost the same. Therefore, apart from the propagation loss, the sharp corner does not introduce extra loss in transmission. Second, this waveguiding band lies within the photonic band gap of the surface wave photonic crystal.³³ Surface waves propagate only along the defect line without penetrating into the bulk of surface wave photonic crystal, thus suppressing scattering to some extent. Note that this high transmission through a sharp corner is achieved differently from that of the recently proposed photonic topological insulators,^{34–37} which support backscattering-immune topological protected edge states arising from photonic pseudo spins or breaking time-reversal symmetry.

Power splitters are important elements in realizing sub-wavelength interconnections and routing of surface waves. Here, we use this waveguiding mechanism to split surface waves into two arms, as illustrated in the inset of Fig. 5(a). Both the input and output waveguides contain six coupled cavities to construct a T-shaped splitter. As shown in Fig. 5(a), the propagating surface defect modes inside the input CDSW split almost equally into two CDSW output ports for all frequencies within the waveguiding band of surface defect modes. We also measure and simulate the electric field distributions on the T-shaped splitter, as shown in Figs. 5(b) and 5(c), respectively.

In conclusion, we have experimentally demonstrated a waveguiding mechanism to manipulate surface waves at a

FIG. 5. (a) Measured normalized transmission spectra for the T-shaped splitter illustrated in the inset. Surface waves in the input waveguide split equally into two output waveguides. (b) Observed field pattern (E_z) of the T-shaped splitter at 13.5 GHz. Input/output ports are indicated with red arrows. (c) Simulated field pattern (E_z) of the T-shaped splitter at 13.5 GHz.

subwavelength scale. The guiding and bending of surface waves through localized surface defect cavities via near-field coupling are fundamentally different from the conventional spoof surface plasmon waveguides. High transmission of surface waves along a straight waveguide, around a sharp corner, as well as through a T-splitter is directly observed. These results provide opportunities to manipulate surface wave at a subwavelength scale with minimal crosstalk.

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