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Subwavelength wave manipulation in a thin surface-wave band-gap crystal

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It has been recently reported that the unit cell of wire media metamaterials can be tailored locally to shape the flow of electromagnetic waves at subwavelength scales [Lemoult *et al.*, *Nature Physics* 9, 55-60 (2013)]. However, such bulk structures have a thickness of at least the order of wavelength, thus hindering their applications in the on-chip compact plasmonic integrated circuits. Here, based upon a Sievenpiper “mushroom” array [Sievenpiper *et al.*, *IEEE Trans. Microwave Theory Tech.* 47, 2059 (1999)] which is compatible with the standard printed circuit board technology, we propose and experimentally demonstrate the subwavelength manipulation of surface waves on a thin surface-wave band-gap crystal with a thickness much smaller than the wavelength (1/30th of the operating wavelength). Functional devices including T-shaped splitter and sharp bend are constructed with good performance. © 2017 Optical Society of America

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Recently, to control the propagation of electromagnetic waves at the deep-subwavelength scales in plasmonic metamaterials [1], the concepts of locally resonant metamaterials [2-3], which is originally proposed in acoustics [4], and surface-wave band-gap crystals [5-9] were developed with superior deep-subwavelength wave manipulations including broadband high transmission around sharp corners [7] and ultra-slow-wave devices [8]. However, all of the aforementioned plasmonic locally resonant metamaterials and surface-wave band-gap crystals have a major limitation associated with their inherent bulk geometry with thickness of at least the order of the wavelength.

A specific type of plasmonic metamaterials, termed “spoof” or “designer” surface plasmons [10-12], have also led to subwavelength guiding propositions. Later, thin metamaterials

with microwave surface-plasmon-like modes [13] and ultrathin flexible films with conform surface plasmons [14], as well as a chain of ultrathin conducting spirals with super-sub-wavelength surface modes [15] were proposed with a thickness much smaller than the operating wavelength. Yet those designs suffer markedly from serious scattering loss when encountering in-plane sharp corners because of the dramatic momentum mismatch of surface electromagnetic waves before and after passing the sharp corners in an extremely compact space. Though an ultrathin 90-degree sharp bend has been numerically proposed for spoof surface plasmons [16], it only achieves high transmission at low frequencies (where the mode is more like a transmission-line mode) and exhibits rather low transmission at high frequencies (where the mode is more like a surface plasmon mode). Therefore, achieving high-efficiency transmission of surface electromagnetic waves around ultrathin and on-chip sharp bends, which is vital for the miniaturization of integrated circuits, still remains a challenge.

In this work, based on a well-known Sievenpiper “mushroom” structure [17] that was first proposed as a resonant high-impedance surface to suppress surface waves with thickness only a fraction of the wavelength, we show that we can tailor its unit cells (metallic patches) locally to shape the flow of surface waves at subwavelength scales within its surface-wave forbidden band gap. We validate our approaches in experiments demonstrating various components including point defect cavities, line defect waveguide, sharp bend and T-shaped splitter. Transmission spectra and near-field imaging measurements have also been implemented in the microwave frequencies to examine the performance of these functional devices.

We start our experimental demonstration using a medium, as schematically shown in Fig. 1(a), that is composed of square 18- μm -thick copper patch of side length $a = 9 \text{ mm}$ arranged in a square array of periodicity $d = 10 \text{ mm}$. The copper patches are separated from a ground plane by a low loss 1.508 mm thick dielectric layer [Rogers RT/duroid 5880 (Permittivity $\epsilon = 2.2 \pm 0.02$; Loss tangent $\Delta\delta = 0.0009$)]; Each copper patch is connected to the ground plane by a hollow copper via of radius $r = 0.25 \text{ mm}$. The numerical calculation of the band structure of this thin surface-wave band-gap crystal is shown in Fig. 1(b). The

fundamental band is TM band and the second-order band is TE band. The TM band does not reach the TE band edge, but stops below it, forming a forbidden bandgap for surface waves from 5.1 GHz to 6.5 GHz. The TE band slopes upward upon crossing the light line. Thus, a surface-wave forbidden band gap spans from the edge of the TM band to the point where the TE band crosses the light line, as indicated with yellow color in Fig. 1(b).

Fig. 1. (a) Schematic depiction of the “mushroom” structure. (b) Calculated band structure of the thin surface-wave band-gap crystal. Yellow region represents the surface modes forbidden band gap of the thin surface-wave band-gap crystal. (c) Measured near-field transmission spectrum of the thin surface-wave band-gap crystal.

Using a vector network analyzer (R&S@ZVL13) and two homemade monopole antennas placed at opposite sides of the experimental sample, we measured the near-field transmission spectrum of the surface modes supported by the thin surface-wave band-gap crystal, as shown in Fig. 1(c). The measured spectral transmission exhibits a substantial drop from 5.1 GHz to 6.5 GHz, corresponding to the forbidden band gap of the thin surface-wave band-gap crystal revealed in Fig. 1(b). This forbidden band gap for surface waves finds its origin in the local resonance of the metallic patch with subwavelength scale ($a \sim d \sim \lambda_{eff}/4$ and $h \sim \lambda_{eff}/30$, where λ_{eff} is the wavelength in the dielectric substrate), and is therefore radically different from the bandgaps obtain in conventional wavelength-scaled photonic crystals [18], which are governed by the Bragg scattering of waves within the unit cells.

Our goal of the work is to use this thin high-impedance surface to control the propagation of surface electromagnetic waves at the subwavelength scales within the surface-wave forbidden band gap, rather than conventional applications to suppress the surface waves to realize low-profile antennas [17]. To achieve this goal, we start by designing the most basic component that can be used to control electromagnetic waves at the subwavelength scale: a point defect cavity. Owing to the subwavelength periodicity of this surface-wave band-gap crystal under study, removing a metallic patch has no effect, contrary to what would happen in conventional photonic crystals in which the point defect will support a tightly confined cavity mode [19]. However, if we replace one copper patch ($a = 9$ mm) with a slightly smaller one ($a = 8$

mm), its own resonance frequency will rise mainly due to the decrease of the patch dimensions and slightly be modulated by the near-field capacitive coupling between neighboring patches. Thus the resonance frequency of the shrunken patch will fall exactly within the forbidden band gap of the thin surface-wave band-gap crystal supported by the surrounding unchanged copper patches, and a point defect cavity is formed. As shown in Fig. 2(a), we use a monopole antenna as the point source to excite the point defect cavity, and using another monopole antenna as the probe to measure the near-field response spectrum of the point defect cavity [red line in Fig. 2(b)]. It can be seen that a sharp resonance peak is emerged at 5.7 GHz within the surface-wave forbidden band gap of the thin surface-wave band-gap crystal. To visualize the point defect cavity mode, we mapped its spatial distribution of the electromagnetic field (E_z) inside and around the cavity using a 5-mm-long monopole antenna which was able to scan in the horizontal plane 1 mm above the sample, measuring both the amplitude and phase of the resonance wave fields. By stepping the probe with 0.5 mm increment in both x and y directions, a full 2D spatial field map can be obtained experimentally. The measured E_z field distribution of the point defect cavity at 5.7 GHz is shown in Fig. 2(c). The point defect cavity is indicated with black dashed line. The imaged area is 60×60 mm² and the surface electromagnetic field is confined within a $(\lambda_{eff}/3)^2$ area. It can be observed that the surface electromagnetic waves are tightly localized around the point defect cavity and slightly penetrate into the surrounding surface-wave band-gap crystal. The measured mode profile of the point defect cavity exhibits isotropic properties due to the oxidization and fabrication error of the metallic patches. Note that numerical mode profile of the point defect cavity exhibits four-fold rotational symmetry because of the square array of metallic patches [7].

Fig. 2. (a) Fabricated sample of a point defect cavity and its experimental set up. (b) Measured near-field response spectra of the thin surface-wave band-gap crystal with a single point defect (red line) and without any defect (black line). (c) Observed field pattern (E_z) of the point defect cavity at its resonance frequency 5.7 GHz. Black dashed line indicates the point defect cavity.

We now move on to more complex components to manipulate surface waves in subwavelength scale on this thin surface-wave band-gap crystal. We first construct a straight line-defect waveguide, as shown in Fig. 3(a), replacing a row of copper patches by smaller ones akin to our point defect cavity experiment. We first measure its near-field transmission spectrum, as shown in Fig. 3(b) (red line), a narrow waveguiding band emerges from 5.5 GHz to 5.8 GHz within the band gap of the thin surface-wave band-gap crystal. We also plot the transmission spectrum of perfect thin surface-wave band-gap crystal without defect for comparison (black line), which exhibits a wide forbidden band that spans from 5.1 GHz to 6.5 GHz, being consistent with the simulated band structure shown in Fig. 1(b). Measured and simulated maps of the spatial distributions of electric field (E_z component) 1 mm above the sample at 5.7 GHz are presented in Fig. 3(c) and Fig. 3(d), respectively. Evidently, surface waves tunnel from defect to defect, forming a very efficient and subwavelength confined propagation. Note that due to the common feature of the majority of electromagnetic resonators: to be resonant, at least one of the dimension should be commensurate with the wavelength. Hence, in the pioneering work [2], the deep-subwavelength manipulation of electromagnetic waves is only achieved in the transverse plane. While in our thin surface-wave band-gap crystal, the deep-subwavelength wave manipulation is only achieved in the vertical direction and the field confinement in the transverse plane does not occur on “deep” but rather moderate subwavelength dimensions.

Fig. 3. (a) Fabricated sample of the straight line-defect waveguide constructed in the thin surface-wave band-gap crystal. (b) Measured normalized transmission spectrum for a straight line-defect waveguide (red line) and an ideal thin surface-wave band-gap crystal without any defect (black line). (c) Measured (d) simulated field pattern (E_z) of a straight line-defect waveguide at 5.7 GHz.

Owing to the resonant nature of the unit cells in this thin surface-wave band-gap crystal, we can control the flow of surface waves in any given path through tailoring the unit cell locally at subwavelength scales. Thus we can construct various components to manipulate surface waves, i.e., a sharp corner and a T-shaped splitter, as shown in Fig. 4(a) and Fig. 4(d). We first consider a sharp bend with zero bending radius. The measured near-field distributions of the sharp corner is shown in Fig. 4(b), matching well with the simulation results shown in Fig. 4(c). In both the experiment and simulation results, we can see that surface waves can be high-efficiently transmitted through the sharp corner without perceptible radiation and reflection. By comparing the amplitude of E_z field at the input and output of the sharp bend, we evaluate that the normalized transmission through the sharp bend is about 90.4% at 5.7 GHz. The high-efficiency guidance of surface waves around the sharp corners is mainly because of the following two reasons. First, the wide surface-wave band gap of the surrounding this surface-wave band-gap crystal suppresses scattering into the ambient space. This feature is similar to previous wavelength-scale photonic circuits in a photonic crystal [20] with full forbidden band gap. Second, since each copper patch exhibits an eigenmode with four-fold rotational symmetry, the momentum is inherently matched before and after passing the sharp corner, thus surface waves cannot feel the difference between a 90° sharp bend and a straight line-defect waveguide. This mechanism of high-efficient transmission through sharp corners is similar to previous wave manipulation along a line defect in a 3D wire medium metamaterial [2] and the coupled-resonator optical waveguide [21].

Fig. 4. (a) Fabricated sample of a sharp bend in the thin surface-wave band-gap crystal. (b) Observed and (c) simulated field pattern (E_z) of the sharp corner at 5.7 GHz. (d) Fabricated sample of a T-shaped splitter in the thin surface-wave band-gap crystal. (e) Observed and (f) simulated field pattern (E_z) of the T-shaped splitter at 5.7 GHz.

In the following, we construct a T-shaped splitter by connecting two straight line-defect waveguides in this surface-wave band-gap crystal, as shown in Fig. 4(c). An ideal splitter should transmit 50% of the input power into each output. We can observe in both the measured near-field distributions of the T-shaped splitter in Fig. 4(e) and the simulation results in Fig. 4(f) that the input surface

waves are split almost equally by the T-shaped splitter with negligible scattering at the junction of the splitter.

In conclusion, we have proposed and experimentally demonstrated a new thin surface-wave band-gap crystal to control the surface wave propagation at the subwavelength scales. Compared with previous bulk locally resonant metamaterials [2], this structure is much thinner with thickness only a fraction of the wavelength (about $1/40\lambda$) and compatible to standard printed circuit board (PCB) technology [22]. Functional devices such as high-efficiency sharp bend and T-shaped splitter have also been constructed with good performance, both of which cannot be achieved with traditional surface-wave waveguides.

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