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<tr>
<td><strong>Citation</strong></td>
<td>Gao, Z., Gao, F., &amp; Zhang, B. (2016). Multi-directional plasmonic surface-wave splitters with full bandwidth isolation. Applied Physics Letters, 108(11), 111107-.</td>
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<td><strong>Date</strong></td>
<td>2016</td>
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<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/40827">http://hdl.handle.net/10220/40827</a></td>
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View online: http://dx.doi.org/10.1063/1.4944461
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Multi-directional plasmonic surface-wave splitters with full bandwidth isolation

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(Received 16 January 2016; accepted 27 February 2016; published online 17 March 2016)

We present a multidirectional plasmonic surface-wave splitter with full bandwidth isolation experimentally based on coupled defect surface modes in a surface-wave photonic crystal. In contrast to conventional plasmonic surface-wave frequency splitters with polaritonic dispersion relations that overlap at low frequencies, this multidirectional plasmonic surface-wave splitter based on coupled defect surface modes can split different frequency bands into different waveguide branches without bandwidth overlap. Transmission spectra and near-field imaging measurements have been implemented in the microwave frequencies to verify the performance of the multidirectional plasmonic surface-wave splitter. This surface wave structure can be used as a plasmonic wavelength-division multiplexer that may find potential applications in the surface-wave integrated circuits from microwave to terahertz frequencies. © 2016 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4944461]

Plasmonic circuits utilizing surface plasmon polaritons (SPPs) that arise from the coupling between Electromagnetic (EM) waves and collective electronic excitations within conducting materials offer opportunities for the construction of ultra-compact optical components due to their remarkable capability of breaking the diffraction limit.1,2 To control the direction of SPPs (or spoof SPPs at low frequencies)3–10 in plasmonic structures, several schemes have already been proposed in recent years.11–17 For example, the unidirectional SPPs coupler adopting the plasmonic Bragg mirror structure11 or placing different surface waveguide structures on opposite side of slit enable slit-coupled light at different frequencies to be guided in different directions.12–14 Recently, the experimental realization of bidirectional SPPs splitter in the microwave frequencies was reported,15,16 and then, it was extended to a multidirectional surface wave splitter.17 However, all of the aforementioned plasmonic structures as surface wave splitters have a major limitation associated with their intrinsic polaritonic dispersion relations which overlap when they approach the light line, making isolation between different waveguide branches incomplete.18 On the other hand, a recently proposed coupled-defect surface waveguide (CDSW),19 in which the waveguiding is achieved through weak coupling between otherwise tightly localized surface defect cavities, allows shaping the flow of surface waves in an isolated tunable bandwidth.

In this letter, we propose and experimentally realize a CDSW-based multidirectional plasmonic surface-wave splitter without bandwidth overlap among split waveguide branches. The CDSW is achieved through weak coupling between tightly localized surface defect cavities in an otherwise gapped surface-wave photonic crystal.19,20 We shorten multiple rows of metallic pillars alternately with different heights to ensure that surface waves propagate along different CDSW branches in different frequency bands. Unlike conventional plasmonic frequency splitters based on polaritonic dispersion relations,12–18 complete isolation between different branches is achieved in this multidirectional plasmonic splitter. Such structures can be used to split different frequency components of an EM pulse into different directions without bandwidth overlap, working as a plasmonic wavelength-division multiplexer. Full-wave simulations and near-field imaging measurements at microwave frequencies have been performed to validate our approach.

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 \( r = 1.25 \text{ mm} \), height \( H = 5 \text{ mm} \), and period \( d = 5 \text{ mm} \). By performing three-dimensional (3D) Finite Integration Technique (FIT) eigenmode simulations, the band structure of the corresponding infinite surface-wave photonic crystal reveals a surface-wave band gap from 12.6 GHz to 27 GHz.19 To construct a multidirectional plasmonic surface wave splitter, we shorten the pillars alternately to create a defect waveguide with different heights \( h \) in different directions. The periodicity of the CDSW is \( D = 2d \). The four waveguide branches are indicated as black arrow \( (h = 3.8 \text{ mm}) \), red arrow \( (h = 4.1 \text{ mm}) \), blue arrow \( (h = 4.4 \text{ mm}) \), and green arrow \( (h = 4.7 \text{ mm}) \), respectively. We use a monopole antenna to excite the coupled-defect surface modes in this surface-wave photonic crystal, as indicated by a white arrow in Fig. 1(a). The coupled-defect surface modes of the four different CDSWs could be excited at the same time.

We first analyze the dispersion relations of these four different CDSWs that construct the multidirectional plasmonic surface wave splitter. The dispersion relations of CDSW are simulated by the eigenmode solver of commercial software, CST Microwave Studio. A super cell that consists of 7 cylindrical metallic rods in the \( x \) direction and one...
and two half cylindrical metallic rods in the y direction is adopted in the simulation. The center pillar (white dashed circle in Fig. 1(c)) in the super cell is shortened from height \( H = 5 \text{ mm} \) to \( h \) while the other pillars keep unchanged. Periodic boundary condition has been applied in the y direction, and the electric boundary conditions have been used in both the x and z directions. By scanning the phase shift between the periodic boundaries from \( kD = 0 \) to \( kD = \pi \) (first Brillouin zone) with 0.05 \( \pi \) step, for each phase shift, we can get one eigenfrequency for the coupled-defect eigenmode; thus, the dispersion curves in the first Brillouin zone can be obtained. The dispersion curves of the four CDSWs with different heights of the shortened pillars (\( h \)) are shown in Fig. 1(b). Compared with conventional spoof surface plasmons waveguides with polaritonic dispersion relations, which start from the light line and tend to zero group velocity at the Brillouin Zone edge, the dispersion relations of CDSWs are similar to those of coupled resonator optical waveguide (CROW) \(^{20}\) with a shape of sine function centered at the resonance frequency of a single surface defect cavity. The four dispersion curves of CDSWs with different shortened pillar heights are completely separated without overlap. This implies full isolation among different branches of the proposed multidirectional surface wave splitter. When the surface wave frequencies lie within the waveguiding band of one CDSW, the EM waves will be only coupled into and propagate along this CDSW. Thus, surface waves with different frequencies will split into different branches and propagate along different directions. We also show the field patterns of \( E_z \) in the \( xy \), \( xz \), and \( yz \) planes for the eigenmode of CDSW with shortened pillar height \( h = 4.4 \text{ mm} \) in Figs. 1(c)–1(e), respectively. The surface defect modes are highly confined around the shortened pillar (white dashed circle/square) and propagate through weak coupling along the y direction.

To demonstrate the performance of the proposed multidirectional plasmonic surface wave splitter, we first simulate the transmission spectra and surface wave intensity distributions of the frequency splitter using the transient solver of CST Microwave Studio with open boundary conditions, a discrete port is placed at the center of the splitter as the source. The other four discrete ports are placed at the ends of four branches of the splitter to detect the intensity of \( E_z \) field as the transmission spectra (S-parameter), respectively. The simulation results of the transmission spectra detected by the four discrete ports in the frequency range from 10 GHz to 15 GHz are shown in Fig. 2(a), being consistent with the dispersion curves in Fig. 1(b). It can be seen that surface waves with different frequencies are completely separated into different waveguiding bands without overlap. The simulated transmission spectrum (grey solid line) of a perfect surface wave photonic crystal without defects is also shown in Fig. 2(a) for comparison, which exhibits a band gap from 12.6 GHz (the upper edge of the band gap at 27 GHz is not shown here). \(^{19}\) The simulated \( E_z \) intensity patterns on a transverse \( xy \) plane 2 mm above the top of 5.0-mm-high aluminum rods of the plasmonic splitter at 12.65 GHz, 13.15 GHz, 13.68 GHz, and 14.28 GHz are shown in Figs. 2(b)–2(e), respectively. Both the source and probes are indicated with white arrows. We can observe that four coupled defect surface modes within different CDSW waveguiding bands are fully split into four branches with different shortened pillars.

We then start to experimentally demonstrate this multidirectional plasmonic surface wave splitter at microwave frequencies. We fabricate a square array of 25 \( \times \) 25 lattice of cylindrical aluminum rods, each having radius \( r = 1.25 \text{ mm} \).
and height $H = 5.0 \text{ mm}$. All rods stand on a flat aluminum plate, which is $125 \text{ mm} \times 125 \text{ mm}$ in size and $5.0 \text{ mm}$ thick. The excitation source is a monopole antenna. The field intensity pattern of $E_z$ component is recorded with a $3 \text{ mm}$-in-length monopole probe, which is mounted on a two-dimensional (2D) translation stage, scanning $2 \text{ mm}$ above the top of the structured metal surface in the $xy$ plane. Both the monopole source and probe are connected to a vector network analyzer (R&S ZVL-13) to measure the S-parameters at a given point. The measured transmission spectra for the four different branches are shown in Fig. 3(a), which confirm the four fully isolated coupled-defect surface mode waveguiding bands for this 4-way surface wave splitter. We also measure the transmission spectrum of the perfect surface-wave photonic crystal (grey solid line) for comparison, which shows a wide forbidden band that starts from $12.85 \text{ GHz}$, $13.35 \text{ GHz}$, $13.88 \text{ GHz}$, and $14.48 \text{ GHz}$ within different CDSW waveguiding bands, respectively.

We adopt a near-field scanning technique to map the local $E_z$ field intensity distributions on the splitter. Figs. 3(b)–3(e) show the measured $E_z$ field intensity distributions excited by a monopole source (white arrow) on a transverse $xy$ plane $2 \text{ mm}$ above the top of the 5.0-mm-high aluminum rods of the plasmonic splitter at frequency $12.85 \text{ GHz}$, $13.35 \text{ GHz}$, $13.88 \text{ GHz}$, and $14.48 \text{ GHz}$, respectively. The measured results agree well with the simulated patterns (Figs. 2(b)–2(e)). It can be observed that highly confined surface waves with different frequencies propagate along different directions with full isolation among waveguide branches.

In conclusion, we have proposed and experimentally demonstrated multidirectional plasmonic surface wave splitters with complete isolation among waveguide branches in the microwave frequencies. This device employs coupled defect surface waveguiding rather than conventional spoof surface plasmon waveguiding with polaritonic dispersion relations. Thus, the coupled defect waveguiding bands of the four different branches of the splitter can be completely...
separated without overlap. Four different CDSWs are introduced by alternately shortening pillar heights on four opposite sides of the monopole source to confine and guide surface waves at different frequencies along different directions with perfect isolation. Transmission spectra and near-field imaging measurements are conducted at microwave frequencies to verify this concept. This multidirectional plasmonic surface wave splitter can be useful for the integrated plasmonic circuits from microwave to terahertz frequencies.

This work was sponsored by the NTU-NAP Start-Up Grant, Singapore Ministry of Education under Grant Nos. MOE2015-T2-1-070 and MOE2011-T3-1-005.

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