Multi-directional plasmonic surface-wave splitters with full bandwidth isolation

Gao, Zhen; Gao, Fei; Zhang, Baile

2016

Gao, Z., Gao, F., & Zhang, B. (2016). Multi-directional plasmonic surface-wave splitters with full bandwidth isolation. *Applied Physics Letters*, 108(11), 111107-.

<https://hdl.handle.net/10356/81499>

<https://doi.org/10.1063/1.4944461>

© 2016 AIP Publishing LLC. This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of AIP Publishing LLC. The published version is available at: [<http://dx.doi.org/10.1063/1.4944461>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 21:20:05 SGT

Multi-directional plasmonic surface-wave splitters with full bandwidth isolation

Zhen Gao, Fei Gao, and Baile Zhang

Citation: [Applied Physics Letters](#) **108**, 111107 (2016); doi: 10.1063/1.4944461

View online: <http://dx.doi.org/10.1063/1.4944461>

View Table of Contents: <http://scitation.aip.org/content/aip/journal/apl/108/11?ver=pdfcov>

Published by the [AIP Publishing](#)

Articles you may be interested in

[Guiding, bending, and splitting of coupled defect surface modes in a surface-wave photonic crystal](#)

Appl. Phys. Lett. **108**, 041105 (2016); 10.1063/1.4940906

[High-efficiency transition between rectangular waveguide and domino plasmonic waveguide](#)

AIP Advances **5**, 027105 (2015); 10.1063/1.4907879

[Compact and broadband directional coupling and demultiplexing in dielectric-loaded surface plasmon polariton waveguides based on the multimode interference effect](#)

Appl. Phys. Lett. **103**, 061108 (2013); 10.1063/1.4817860

[Multidirectional surface-wave splitters](#)

Appl. Phys. Lett. **98**, 221901 (2011); 10.1063/1.3595281

[Plasmonic surface-wave splitter](#)

Appl. Phys. Lett. **90**, 161130 (2007); 10.1063/1.2731524

The advertisement for MMR Technologies features a blue and white background with a grid pattern. On the left is the MMR Technologies logo, which consists of the letters 'MMR' in a bold, sans-serif font, with 'TECHNOLOGIES' in a smaller font below it, all enclosed within a stylized circular graphic. To the right of the logo, the text 'THE WORLD'S RESOURCE FOR VARIABLE TEMPERATURE SOLID STATE CHARACTERIZATION' is displayed in a bold, sans-serif font. Below this text, there are five images of different scientific instruments: a small electronic device, a larger electronic device labeled 'SB1000' and 'K2000', a circular microprobe station, a rectangular electronic device labeled 'H5000' and 'K2000', and a large, complex mechanical system. At the bottom of the advertisement, the website 'WWW.MMR-TECH.COM' is listed on the left, and the names of the instrument categories are listed on the right: 'OPTICAL STUDIES SYSTEMS', 'SEEBECK STUDIES SYSTEMS', 'MICROPROBE STATIONS', and 'HALL EFFECT STUDY SYSTEMS AND MAGNETS'.

Multi-directional plasmonic surface-wave splitters with full bandwidth isolation

Zhen Gao,¹ Fei Gao,¹ and Baile Zhang^{1,2,a)}

¹*Division of Physics and Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 637371, Singapore*

²*Centre for Disruptive Photonic Technologies, Nanyang Technological University, Singapore 637371, Singapore*

(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 $r = 1.25$ mm, height $H = 5$ mm, and period $d = 5$ 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 ($h = 3.8$ mm), red arrow ($h = 4.1$ mm), blue arrow ($h = 4.4$ mm), and green arrow ($h = 4.7$ 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

^{a)} Author to whom correspondence should be addressed. Electronic mail: blzhang@ntu.edu.sg

FIG. 1. (a) Photograph of the multidirectional plasmonic surface wave splitter realized on a structured metal surface (surface-wave photonic crystal) that consists of a square array of cylindrical aluminum pillars with radius $r = 1.25$ mm, height $H = 5$ mm, and periodicity $d = 5$ mm. The periodicity of CDSW is $D = 2d$. Four different coupled defect surface waveguides with various alternately shortened pillars height are indicated as black ($h = 3.8$ mm), red ($h = 4.1$ mm), blue ($h = 4.4$ mm), and green ($h = 4.7$ mm) arrows, respectively. A monopole source (white arrow) is adopted to excite the perfect multidirectional surface wave splitter. (b) Calculated dispersion relations for four different coupled defect surface waveguides that construct the multidirectional surface wave splitter. (c)–(e) Simulated E_z field distributions of the eigenmode of CDSW in xy , xz , and yz planes at the edge of the first Brillouin zone with shortened pillar height $h = 4.4$ mm.

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 $H = 5$ 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 0.05π 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 $h = 4.4$ 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 25×25 lattice of cylindrical aluminum rods, each having radius $r = 1.25$ mm

FIG. 2. (a) Simulated transmission spectra of the four branches of the multidirectional surface wave splitter. The transmission spectrum of a perfect surface wave photonic crystal (grey solid line) is also shown for comparison. All four waveguiding bands of CDSW that consists of the multidirectional surface wave splitter are located in the photonic band gap of the surface wave photonic crystal. (b)–(e) Simulated E_z field intensity distributions on a transverse xy plane 2 mm above the splitter for four different frequencies 12.65 GHz, 13.15 GHz, 13.68 GHz, and 14.28 GHz within different CDSW waveguiding bands, respectively.

and height $H = 5.0$ mm. All rods stand on a flat aluminum plate, which is $125\text{ mm} \times 125\text{ mm}$ in size and 5.0 mm thick. The excitation source is a monopole antenna. The field intensity pattern of E_z component is recorded with a 3 mm-in-length monopole probe, which is mounted on a two-dimensional (2D) translation stage, scanning 2 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 dotted line) for comparison, which shows a wide forbidden band that starts from 12.6 GHz, being consistent with the band structure shown in Ref. 19. Note that the simulated transmission spectra (Fig. 2(a)) and the measured transmission spectra (Fig. 3(a)) has a 0.2 GHz shift that is consistent in all transmission bands. This discrepancy mainly comes from the fabrication imperfection, including metallic loss, surface oxidization, and moisture adhesion. However, as the frequency shift for all

FIG. 3. Measured transmission spectra of the four branches of the multidirectional surface wave splitter. The transmission spectrum of a perfect surface wave photonic crystal (grey dotted line) is also measured for comparison. All the four waveguiding bands of CDSW that consists of the surface wave splitter are located in the photonic band gap of the surface wave photonic crystal. (b)–(e) Measured E_z field intensity distributions on a transverse xy plane 2 mm above the splitter for four different frequencies 12.85 GHz, 13.35 GHz, 13.88 GHz, and 14.48 GHz within different CDSW waveguiding bands, respectively.

transmission bands is about 0.2 GHz, this discrepancy caused by fabrication imperfection is consistent in our measurement.

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 mm above the top of 5.0-mm-high aluminum rods of the plasmonic splitter at frequency 12.85 GHz, 13.35 GHz, 13.88 GHz, and 14.48 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.

- ¹W. L. Barnes, A. Dereux, and T. W. Ebbesen, *Nature (London)* **424**, 824 (2003).
- ²E. Ozbay, *Science* **311**, 189 (2006).
- ³A. F. Harvey, *IRE Trans. Microwave Theory Tech.* **8**, 30–61 (1960).
- ⁴J. B. Pendry, L. Martín-Moreno, and F. J. Garcia-Vidal, *Science* **305**, 847–848 (2004).

- ⁵D. Martín-Cano, M. L. Nesterov, A. I. Fernandez-Dominguez, F. J. Garcia-Vidal, L. Martín-Moreno, and E. Moreno, *Opt. Express* **18**, 754–764 (2010).
- ⁶Z. Gao, X. F. Zhang, and L. F. Shen, *J. Appl. Phys.* **108**, 113104 (2010).
- ⁷Z. Gao, L. F. Shen, and X. D. Zheng, *IEEE Photonics Technol. Lett.* **24**, 1343–1345 (2012).
- ⁸Z. Gao, L. Shen, J.-J. Wu, T.-J. Yang, and X. Zheng, *Opt. Commun.* **285**, 2076 (2012).
- ⁹X. P. Shen, T. J. Cui, D. Martín-Cano, and F. J. Garcia-Vidal, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 40–45 (2013).
- ¹⁰F. Gao, Z. Gao, X. Shi, Z. Yang, X. Lin, J. D. Joannopoulos, M. Soljacic, H. Chen, L. Lu, Y. Chong, and B. Zhang, e-print [arXiv:1504.07809](https://arxiv.org/abs/1504.07809).
- ¹¹F. López-Tejiera, S. G. Rodrigo, L. Martín-Moreno, F. J. García-Vidal, E. Devaux, T. W. Ebbesen, J. R. Krenn, I. P. Radko, S. I. Bozhevolnyi, M. U. González, J. C. Weeber, and A. Dereux, *Nat. Phys.* **3**, 324 (2007).
- ¹²Q. Gan, B. Guo, G. Song, L. Chen, Z. Fu, Y. J. Ding, and F. J. Bartoli, *Appl. Phys. Lett.* **90**, 161130 (2007).
- ¹³Q. Gan, Z. Fu, Y. J. Ding, and F. J. Bartoli, *Opt. Express* **15**, 18050 (2007).
- ¹⁴Q. Gan and F. J. Bartoli, *Opt. Lett.* **35**, 4181 (2010).
- ¹⁵H. Caglayan and E. Ozbay, *Opt. Express* **16**, 19091 (2008).
- ¹⁶Y. J. Zhou, Q. Jiang, and T. J. Cui, *Opt. Express* **19**, 5260 (2011).
- ¹⁷Y. J. Zhou and T. J. Cui, *Appl. Phys. Lett.* **98**, 221901 (2011).
- ¹⁸Y. J. Zhou, X. X. Yang, and T. J. Cui, *J. Appl. Phys.* **115**, 123105 (2014).
- ¹⁹Z. Gao, F. Gao, and B. Zhang, *Appl. Phys. Lett.* **108**, 041105 (2016).
- ²⁰A. Yariv, Y. Xu, R. K. Lee, and A. Scherer, *Opt. Lett.* **24**, 711 (1999).