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Experimental demonstration of a band-notched line-defect waveguide in a surface-wave photonic crystal

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We propose and experimentally demonstrate a band-notched line-defect waveguide in a surface-wave photonic crystal, which consists of a straight line-defect waveguide and side-coupled defect cavities. A narrow stop band can be observed in the broadband transmission spectra. We also demonstrate that both the filtering levels and filtering frequencies of the band-notched line-defect waveguide can be adjusted through changing the number and the height of metallic pillars of the side-coupled defect cavities. The band-notch function is based on the idea that the propagating surface modes with the resonance frequencies of the side-coupled defect cavities will be tightly localized around the defect sites, being filtered from the waveguide output. Transmission spectra measurements and direct near-field profile imaging are performed at microwave frequencies to verify our design. These results may enable various band-notched devices applications and provide routes for the realization of surface-wave filters on a single metal surface. *Published by AIP Publishing.*

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Surface plasmons (SPs) are electron density waves excited at the interfaces between metal and dielectric materials.¹ Owing to their tightly localized electromagnetic fields, they are deemed promising candidates for the manipulation of photons on subwavelength scales.^{2,3} Generally, SPs exist in the form of either surface plasmon polaritons (SPPs) as propagation surface modes⁴ or localized surface plasmon polaritons (LSPs) as resonance modes.⁵ To overcome the loss limitation and export the properties of SPPs and LSPs to low frequencies (middle-infrared to far-infrared, terahertz, and microwave), both the concepts of spoof-SPPs^{6–9} and spoof-LSPs^{10–15} have been proposed separately by patterning the extended metal surface or closed metal surface with sub-wavelength periodic features. More recently, by merging the band gap concept of photonic crystals (PCs)¹⁶ and the deep-subwavelength nature of plasmonic metamaterials,^{6,17} the concepts of hybrid locally resonant metamaterials^{18,19} and surface-wave photonic crystals^{20–24} have been developed to manipulate electromagnetic waves in deep-subwavelength scales with superior properties such as broadband high transmission through sharp bends,²² high-Q open resonators,²² and slow wave devices.²³

In this Letter, we move one step further and realize a band-notch function for waveguiding in a surface-wave photonic crystal. We study the resonant transmission of surface waves in a band-notched line-defect waveguide. This band-notched line-defect waveguide is formed by coupling a line-defect waveguide with side-coupled defect cavities in a surface-wave photonic crystal.²² We observe that an adjustable stop band can be generated in the broadband transmission spectra of the line-defect waveguide by changing the

cylindrical pillar height and the total number of the side-coupled defect cavities. The transmission spectra are measured and the near-field profiles of the transmission dips are imaged directly at microwave frequencies to verify our design. This band-notched line-defect waveguide can be conveniently implemented on a single metal surface. It can be useful as a notch filter in the future integrated plasmonic circuits in both terahertz and far infrared frequency ranges.

The proposed band-notched line-defect waveguide is constructed in a surface-wave photonic crystal,²² as shown in Fig. 1(a). The surface-wave photonic crystal consists of a square array (25×25) of circular aluminum pillars with periodicity $d = 5.0$ mm, height $H = 5.0$ mm, and radius $r = 1.25$ mm, all standing on a flat metallic surface. Such surface-wave photonic crystals can exhibit complete forbidden band gaps for surface waves.^{20,24} Previous Finite Integration Technique (FIT) eigenmode simulation has revealed a complete surface modes band gap from 12.6 GHz to 27 GHz for the current setup.²⁰ A straight line-defect waveguide can be constructed by shortening the height of a row of aluminum pillars in the middle from $H = 5.0$ mm to $h = 4.3$ mm, as indicated by a long white line in Fig. 1(a). The calculated dispersion of the straight line-defect waveguide (red line) is shown in Fig. 1(b) with the purple region representing the forbidden band gap of the surface-wave photonic crystal. Fig. 1(c) shows the eigenmode field distributions (E_z) of the line-defect waveguide in a vertical yz plane and a transverse xy plane, respectively. The surface line-defect modes are highly confined around the shortened pillar (white dashed circle/square) and propagate along the x direction. Using two monopole antennas connected to a vector network analyzer (R&S ZVL-13) as the source and probe, we also measured the transmission spectrum of the line-defect waveguide (red line), as shown in Fig. 1(d). A broad transmission band starting from 12.6 to

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FIG. 1. (a) Photography of the band-notched line-defect waveguide in a surface-wave photonic crystal that consists of a straight line-defect waveguide (long white line) with shortened pillar height h and side-coupled point defect cavities (white dots). The surface-wave photonic crystal consists of a square array of circular aluminum pillars with radius $r = 1.25$ mm, height $H = 5$ mm, and periodicity $d = 5$ mm, all standing on a flat aluminum surface. The line-defect waveguide is constructed by shortening a row of pillars from $H = 5$ mm to $h = 4.3$ mm. And the side-coupled point defect cavities (white dots) are created by shortening several side pillars from H to h_c . (b) Dispersion of the line-defect waveguide with shortened pillar height $h = 4.3$ mm. Purple region represents the forbidden band gap of the surface-wave photonic crystal. (c) Eigen mode field distributions (E_z) of the line-defect waveguide in a vertical yz plane and a transverse xy plane. (d) Measured transmission spectrum of the line-defect waveguide (red line) and a perfect surface-wave photonic crystal (grey line). Inset shows the measured E_z field distribution at 13.5 GHz in a transverse xy plane 1 mm above a straight line-defect waveguide.

14.2 GHz can be observed. We also measured the transmission spectrum of a perfect surface-wave photonic crystal without defects (grey line) for comparison. Using a robotic translation stage to move the probe in a transverse xy plane 1 mm above the line-defect waveguide, we map its near-field distribution (E_z), as shown in the inset of Fig. 1(d). It can be seen that tightly confined surface waves can be guided along the line-defect waveguide in a broad frequency range within the photonic band gap of the surrounding surface-wave photonic crystal. Note that similar results have been demonstrated in Ref. 22.

Now we move on to realize a band notch function in this surface-wave photonic crystal by introducing side-coupled defect cavities with shortened pillar height $h_c = 4.3$ mm along the line-defect waveguide, as shown in Fig. 1. The underlying mechanism of this band-notch function is exactly the analog of the channel drop filters in conventional photonic crystals.^{25–27} The line-defect waveguide (wide white line) couples with several side point defect cavities (white dots). While line-defect surface modes (multi-frequency) propagate along the line-defect waveguide, a single-frequency surface mode (at the resonance frequency of the side-coupled defect cavity) is coupled and tightly trapped by the side-coupled defect cavities, thus inducing a band notch in the transmission spectra of the straight line-defect waveguide. This is very similar with the channel drop filters that have been extensively studied in conventional photonic crystals.^{25–27}

Since this surface-wave photonic crystal structure is assembled by inserting machined metallic pillars into a machined metal surface with square array of holes, thus we can change the metallic pillars with different heights

conveniently to introduce different defect cavities. We first simulate the transmission spectra and near-field distributions (E_z) of the band-notched filter with different number of side-coupled defect cavities ($N = 2, 4, 6, 8, 10$, respectively) using the transient solver of CST Microwave Studio with open boundary conditions. A discrete port is placed at the input of the filter as the source. The other discrete port is placed at the output of the filter to detect E_z field as the transmission spectra (S-parameter S_{21}). The simulation results of the transmission spectra detected by the probe discrete port in the frequency range from 12 GHz to 15 GHz are shown in Fig. 2(a) with the enlarged transmission dips shown as the inset. Here, the solid line with different colors are the transmission coefficients of the straight line-defect waveguide without any side-coupled defect cavities (red line), and the band-notched filter with different number of side-coupled defect cavities: $N = 2$ (gray line), $N = 4$ (blue line), $N = 6$ (magenta line), $N = 8$ (cyan line), and $N = 10$ (olive line), respectively. The introduced side-coupled defect cavities form a very narrow transmission dip in the broadband transmission spectrum of the line-defect waveguide (red line) at almost the same frequency which is exactly the resonant frequency of the side-coupled defect cavities. Note that the small perturbation of the frequencies of the resonant transmission dips is a result of interaction among the point defect cavities and the line-defect waveguide. As the total number of side-coupled defect cavities increase, very narrow transmission dips occur with enhanced filtering levels. It can be seen that the transmission coefficient (S_{21}) is less than -10 dB at the transmission dip of the band notch filter with two side-coupled defect cavities (gray line) and further

FIG. 2. (a) Simulated transmission spectra of the band-notched line-defect waveguides with different number of side-coupled defect cavities ($N=2, 4, 6, 8, 10$, respectively). The simulated transmission spectrum of a straight line-defect waveguide without any side-coupled defect cavities (red line) is also shown for comparison. Inset shows the enlarged transmission dips. (b)–(f) Simulated field patterns (E_z) of the band-notched line-defect waveguide with different side-coupled defect cavities ($N=2, 4, 6, 8, 10$, respectively) in a transverse xy plane 1 mm above the top of 5.0-mm-high pillars of the surface-wave photonic crystal at their resonant transmission dip frequencies.

reduces to -28 dB with ten side-coupled defect cavities (olive line). The transmission spectra keep near 0 dB outside the stop band for all band-notched filters. The filtering level of the band-notched line-defect waveguides is rising with increasing the total number of the side-coupled defect cavities. The simulated field distributions of E_z component in a transverse xy plane 1 mm above the top surface of 5-mm-high pillars at the transmission dips of the band-notched line-defect waveguides with different number of side-coupled defect cavities are shown in Figs. 2(b)–2(f), respectively, exhibiting strong field confinement and localization around the side-coupled defect sites. The input surface waves are coupled and

tightly localized by the side-coupled defect cavities one by one and the output surface waves are decreased with increasing the number of side-coupled defect cavities, indicating the adjustability of the filtering level of the band-notched line-defect waveguide.

From now on, we fix the number of side-coupled defect cavities as $N=10$ and demonstrate the adjustability of filtering frequencies of the band-notched line-defect waveguides by changing the pillar height of the side-coupled defect cavities h_c . We use the same simulation method to study three different band-notched line-defect waveguides with three different pillar heights ($h_c = 4.2, 4.3$, and 4.4 mm, respectively) of side-coupled defect cavities, as schematically shown in the inset of Fig. 3(a). The simulated transmission spectra of the band-notched filter with different pillar heights of side-coupled defect cavities are shown in Fig. 3(a). It can be seen that all three transmission spectra contain one dominant feature: a resonant transmission dip. This feature shifts to lower frequencies as the aluminum pillar height of the ten side-coupled defect cavities increases from $h_c = 4.2$ mm (blue line) to $h_c = 4.3$ mm (olive line) and $h_c = 4.4$ mm (purple line), indicating the adjustability of filtering frequencies of the band-notched line-defect waveguides. The simulated transmission spectrum (red line) of a straight line-defect waveguide without any side-coupled defect cavities is also shown in Fig. 3(a) for comparison, which exhibits a broadband transmission from 12.5 GHz to 13.8 GHz without any dips. The simulated E_z field patterns on a transverse xy plane 1 mm above the top surface of 5.0-mm-high aluminum rods of the band-notched filter at three different resonant transmission dips are shown in Figs. 3(b)–3(d), respectively. Both the source and probe are indicated with black arrows. We can observe that, at the resonant transmission dip frequencies, the ten side-coupled defect cavities are excited and the propagating electromagnetic energy is gradually coupled and localized by the side-coupled defect cavities one by one along the propagation direction, exhibiting strong field confinement and localization around the side-coupled defects. In Fig. 3(c), since the pillar height of the side-coupled defect cavities ($h_c = 4.3$ mm) matches that in the line-defect waveguide ($h = 4.3$ mm), we notice that the field amplitude in the side-coupled defect cavities is almost the same as that in the

FIG. 3. (a) Simulated transmission spectra of the band-notched line-defect waveguides with different pillar heights of side-coupled defect cavities ($h_c = 4.2, 4.3, 4.4$ mm, respectively). The simulated transmission spectrum of a straight line-defect waveguide without side-coupled defect cavities (red line) is also shown for comparison. Inset illustrates the band-notched line-defect waveguide configuration. (b) Simulated field pattern (E_z) of a band-notched line-defect waveguide with side-coupled defect cavities pillar height (b) $h_c = 4.2$ mm at the frequency (13.3 GHz) of the transmission dip, (c) $h_c = 4.3$ mm at the frequency (13.1 GHz) of the transmission dip, (d) $h_c = 4.4$ mm at the frequency (12.9 GHz) of the transmission dip.

FIG. 4. (a) Measured transmission spectra of the band-notched line-defect waveguides with different pillar heights of side-coupled defect cavities ($h_c = 4.2, 4.3, 4.4$ mm, respectively). The measured transmission spectrum of a straight line-defect waveguide without any side-coupled defect cavities (red line) is also shown for comparison. Inset shows the band-notched line-defect waveguide configuration. (b) Measured field profile (E_z) of a band-notched line-defect waveguide with side-coupled defect cavities pillar height $h_c = 4.2$ mm at 13.6 GHz, (c) $h_c = 4.3$ mm at 13.4 GHz, and (d) $h_c = 4.4$ mm at 13.2 GHz.

line-defect waveguide. However, the situation is different in Fig. 3(b) ($h_c = 4.2$ mm) and Fig. 3(d) ($h_c = 4.4$ mm), where the pillar height of the side-coupled defect cavities does not match with that in the line-defect waveguide. For Fig. 3(b), the field amplitude of surface waves in the line-defect waveguide is slightly smaller than that of the side-coupled defect cavities, while for Fig. 3(d), the field amplitude of surface waves in the line-defect waveguide is slightly larger than that of the side-coupled defect cavities.

To validate our design, we used the same experimental setup to measure the transmission spectra (S-parameters S21) of the band-notched filters in the frequency range from 10 to 15 GHz. Two homemade monopole antennas, serving as the source and the probe, respectively, were placed next to the input and the output of the band-notched line-defect waveguide, as illustrated as red arrows in the inset of Fig. 4(a). We first measured the transmission spectrum (red line in Fig. 4(a)) of a straight line-defect waveguide without any side-coupled defect cavities. Then, we measured the transmission spectra of the band-notched line-defect waveguides with three different side-coupled defect cavity pillar heights. One clear resonant transmission dip can be observed in the transmission spectrum for each band notch filter. The measured near-field distributions (E_z) in a transverse xy plane 1 mm above the top of 5.0-mm-high aluminum rods of the band-notched filter at three different resonant transmission dips are shown in Figs. 4(b)–4(d), respectively, which match well with the simulation results in Figs. 3(b)–3(d). We can observe that the surface waves are gradually coupled and tightly localized by the side-coupled defect cavities and filtered from the waveguide output. Note that the simulated transmission spectra (Fig. 3(a)) and the measured transmission spectra (Fig. 4(a)) have 0.3 GHz shift that is consistent in all transmission bands. This discrepancy mainly comes from the fabrication imperfection. However, as the frequency shift for all transmission bands is about 0.3 GHz, this discrepancy caused by fabrication imperfection is consistent in our measurement. Note that the discrepancy between the measured near-field profiles (Figs. 4(b)–4(d)) and the simulated near-field profiles (Figs. 3(b)–3(d)) is mainly a result of the propagation loss that arises from the metallic absorption and experimental imperfection. Because of the propagation loss, the measured field maximum is always at the input of the

band-notched line-defect waveguide (Figs. 4(b)–4(d)), but it is not always the case in simulation (Figs. 3(b)–3(d)).

In conclusion, we have experimentally demonstrated a band-notched line-defect waveguide in a surface-wave photonic crystal at microwave frequencies. Owing to the adjustability of the surface-wave photonic crystal, we were able to achieve different resonant transmission dips with different filtering frequencies and filtering levels in the transmission spectra of the notch filter by changing the pillar height and total number of the side-coupled defect cavities. Transmission spectra measurements and direct near-field profiles imaging performed at microwave frequencies verify our design. Finally, we would like to emphasize that our design is very general and can be applied to other frequency ranges such as terahertz and infrared frequencies.

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- ¹W. L. Barnes, A. Dereux, and T. W. Ebbesen, *Nature* **424**, 824 (2003).
- ²E. Ozbay, *Science* **311**, 189–193 (2006).
- ³S. I. Bozhevolnyi, V. S. Volkov, E. Devaux, J. Y. Laluet, and T. W. Ebbesen, *Nature (London)* **440**, 508–511 (2006).
- ⁴T. W. Ebbesen, C. Genet, and S. I. Bozhevolnyi, *Phys. Today* **61**(5), 44 (2008).
- ⁵K. A. Willets and R. P. Van Duyne, *Annu. Rev. Phys. Chem.* **58**, 267 (2007).
- ⁶J. B. Pendry, L. Martín-Moreno, and F. J. Garcia-Vidal, *Science* **305**, 847–848 (2004).
- ⁷A. P. Hibbins, B. R. Evans, and J. R. Sambles, *Science* **308**, 670–672 (2005).
- ⁸D. 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).
- ⁹X. P. Shen, T. J. Cui, D. Martín-Cano, and F. J. Garcia-Vidal, *Proc. Natl. Acad. Sci.* **110**, 40–45 (2013).
- ¹⁰A. Pors, E. Moreno, L. Martín-Moreno, J. B. Pendry, and F. J. Garcia-Vidal, *Phys. Rev. Lett.* **108**, 223905 (2012).
- ¹¹X. P. Shen and T. J. Cui, *Laser Photonics Rev.* **8**, 137–145 (2014).
- ¹²F. Gao, Z. Gao, X. H. Shi, Z. J. Yang, X. Lin, and B. L. Zhang, *Opt. Express* **23**, 6896–6902 (2015).
- ¹³F. Gao, Z. Gao, Y. M. Zhang, X. H. Shi, Z. J. Yang, and B. L. Zhang, *Laser Photonics Rev.* **9**, 571–576 (2015).
- ¹⁴Z. Gao, F. Gao, K. K. Shastri, and B. L. Zhang, *Sci. Rep.* **6**, 25576 (2016).
- ¹⁵Z. Gao, F. Gao, H. Y. Xu, Y. M. Zhang, and B. L. Zhang, *Opt. Lett.* **41**, 002181 (2016).
- ¹⁶J. D. Joannopoulos, R. D. Meade, and J. N. Winn, *Photonic Crystals: Molding the Flow of Light* (Princeton University Press, 2008).

- ¹⁷J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, *Phys. Rev. Lett.* **76**, 4773 (1996).
- ¹⁸F. Lemoult, N. Kaina, M. Fink, and G. Lerosey, *Nat. Phys.* **9**, 55–60 (2013).
- ¹⁹N. Kaina, F. Lemoult, M. Fink, and G. Lerosey, *Appl. Phys. Lett.* **102**, 144104 (2013).
- ²⁰Z. Gao, F. Gao, and B. L. Zhang, *Appl. Phys. Lett.* **108**, 041105 (2016).
- ²¹Z. Gao, F. Gao, and B. L. Zhang, *Appl. Phys. Lett.* **108**, 111107 (2016).
- ²²Z. Gao and B. L. Zhang, e-print [arXiv:1604.06872](https://arxiv.org/abs/1604.06872).
- ²³N. Kaina, A. Causier, Y. Bourlier, M. Fink, T. Berthelot, and G. Lerosey, e-print [arXiv:1604.08117](https://arxiv.org/abs/1604.08117).
- ²⁴S. H. Kim, S. S. Oh, K. J. Kim, J. E. Kim, H. Y. Park, O. Hess, and C. S. Kee, *Phys. Rev. B* **91**, 035116 (2015).
- ²⁵S. H. Fan, P. R. Villeneuve, and J. D. Joannopoulos, *Opt. Express* **3**, 4 (1998).
- ²⁶Y. Akahane, T. Asano, B.-S. Song, and S. Noda, *Nature* **425**, 944 (2003).
- ²⁷Y. Akahane, T. Asano, B.-S. Song, and S. Noda, *Appl. Phys. Lett.* **83**, 1512 (2003).