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Experimental demonstration of Fabry-Perot open resonators in a surface-wave bandgap crystal

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We report on the proposal and experimental realization of a type of retardation-based Fabry-Perot (FP) open resonator in a surface-wave bandgap crystal implemented on a single structured metal surface. This surface-wave FP open resonator is formed by introducing a finite line defect in the surface-wave bandgap crystal, whose resonance frequencies lie exactly within the forbidden bandgap of the surrounding crystal. Due to the complete surface-wave forbidden bandgap, a new FP plasmonic resonance mode exhibiting monopolar features which is missing in both traditional FP resonators and plasmonic resonators is emerged. Near-field response spectra and imaged mode profiles are presented to characterize the properties of these FP open resonators in the microwave regime. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4993300>]

Surface plasmons (SPs), or surface electromagnetic waves that strongly couple to free electron oscillations at a metal-dielectric interface,¹ are deemed promising candidates for the transport and manipulation of photons on subwavelength scales^{2–4} owing to their tightly localized electromagnetic fields. In general, SPs exist either as propagating surface plasmon polaritons (SPPs) on an extended metal surface¹ or as localized surface plasmon polaritons (LSPs) on a finite metal surface, i.e., plasmonic particles.⁴ In particular, such electron-photon coupled resonances, well known as localized surface plasmon resonances (LSPRs) on plasmonic particles, have resulted in unique and promising applications in photonic and biosensing technology.⁴

Generally, plasmonic particles with finite metal surfaces can be classified into two types: (1) plasmonic particles with size much smaller than the light wavelength (5–50 nm), where the optical behavior is mainly determined by resonances of dipole character;^{5,6} and (2) elongated plasmonic particles with size comparable to the wavelength (termed as “surface plasmon Fabry-Perot resonators”), which exhibit multipolar FP plasmonic resonance in the longitudinal direction.^{7–9} Recently, to adopt the properties of LSPs to low frequencies (far-infrared, terahertz, and microwave frequencies), the concept of spoof localized surface plasmons (spoof-LSPs) was proposed by periodically texturing plasmonic particles with closed surfaces much smaller than the wavelength¹⁰ and experimentally verified on an ultrathin metallic disk at microwave frequencies.^{11–15}

More recently, by merging the forbidden bandgap of a photonic crystal¹⁶ and the deep subwavelength nature of surface plasmons,^{17–21} the concept of surface-wave bandgap crystal^{22–28} with a subwavelength-scale unit cell was developed with superior properties including multi-directional splitting of surface waves with full bandwidth isolation,²⁵ broadband high transmission through sharp bends,²⁶ and slow wave devices.²⁷

Here, we propose and experimentally demonstrate a type of retardation-based spoof surface plasmon Fabry-Perot open resonator by introducing a finite line defect in a surface-wave bandgap crystal. In contrast to conventional spoof-LSPs supported on textured closed metal surfaces which originate from the interference of clockwise and counterclockwise propagating surface modes,^{10–14} the FP open resonator modes, i.e., standing surface waves tightly localized in the finite line defect, originate from the end-face reflections due to the complete forbidden bandgap of the surrounding surface-wave bandgap crystal for surface modes. Moreover, unlike conventional FP resonators^{7–9,29–31} and plasmonic resonators^{10–15} standing in a homogeneous medium (e.g., air) where waves can propagate, both the field confinement and the quality factors of the spoof surface plasmon FP open resonators are enhanced due to the forbidden bandgap offered by the surrounding surface-wave bandgap crystal. We also demonstrate that the main characteristics of the FP open resonators, the total numbers and the resonance frequencies of the FP resonance modes, can be conveniently engineered through changing the defect numbers (or total length) of the open resonator by replacing the shorter pillars with higher ones rather than changing the whole geometry in a refabrication.

We start with a surface-wave bandgap crystal that consists of a periodic (period $d = 5.0$ mm) 15×15 square lattice of circular metal rods, standing on a flat metallic surface, as shown in Fig. 1. Each rod has a height of $H = 5.0$ mm and a radius of $r = 1.25$ mm. The sample was fabricated with mechanical machining with a tolerance of 0.1 mm and the whole size of 80×80 mm². The calculated band structure for the perfect surface-wave bandgap crystal, as shown in Fig. 2(a), reveals a complete forbidden bandgap for surface waves from 12.6 GHz to 27 GHz (the yellow region).

A vector network analyser (VNA; Agilent Technologies N5225A) and two small near-field homemade antennas were adopted for the measurement. The near-field antennas, serving as the point source and probe, were constructed by cutting a SMA (SubMiniature version A) coaxial cable in such

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FIG. 1. (a) Photograph of the Fabry-Perot open resonators (dashed rectangle) in a surface-wave bandgap crystal that consists of a square array of cylindrical aluminum pillars with radius $r = 1.25$ mm, height $H = 5.0$ mm, and periodicity $d = 5.0$ mm, all standing on a metal surface. The spoof surface plasmon Fabry-Perot open resonators are created by shortening several cylindrical pillars (white dots) from height $H = 5.0$ mm to $h = 4.3$ mm in the middle of the surface-wave bandgap crystal.

a way that a short (5 mm) piece of its core shows up outside of the shielding. Both the point source and probe were oriented along the vertical direction and thus measured only the E_z component of the electric field. In the VNA setup, 1001 points were sampled in the frequency spectrum and the power to 10 dB was set in order to gain a sufficient signal to noise ratio.

At two opposite sides of the surface-wave bandgap crystal (without shortening any metallic rod), we placed the point source and probe to measure the S-parameter (S_{21}) as the relative transmission between the point source and probe. The absolute value of the S_{21} parameter has no practical meaning because of the large impedance mismatch between the point source/probe and the crystal. The measured transmission spectrum supported by the surface-wave bandgap crystal is shown in Fig. 2(b). The measured transmission exhibits a substantial drop in the frequency range from 12.6 GHz to 27 GHz, corresponding to the forbidden bandgap. When the sample was removed, the signal level reduced below -40 dB, which means that negligible energy is received by the probe. Hereafter, all data of transmission and near-field measurements will be normalized.

To realize a spoof surface plasmon FP open resonator, a finite line defect can be constructed by shortening the height of several cylindrical pillars from $H = 5.0$ mm to $h = 4.3$ mm in the middle of the surface-wave bandgap crystal (as illustrated in Fig. 1), and thus, the resonance frequencies of the FP open resonator are located within the forbidden bandgap of the surrounding surface-wave bandgap crystal. We first constructed a finite line defect with seven shortened pillars

($N = 7$) in the middle of the surface-wave bandgap crystal. The experimental setup is shown in the inset of Fig. 3(a). The point source antenna is placed near the first shortened rod to excite the FP open resonator. The point probe antenna near the last shortened rod measures the near-field transmission spectrum (S-parameter S_{21}). The measured spectrum is shown in Fig. 3(b), from which seven resonance peaks marked as M_1 - M_7 can be clearly observed within the bandgap of the surrounding surface-wave bandgap crystal (the yellow region). Note that when we changed the surrounding surface-wave bandgap crystal to perfect electric conductors (PECs) which can also behave as reflectors, the lower order modes (M_1 - M_3) disappeared because PECs do not allow any penetration of evanescent waves. Moreover, FP open resonators with different shapes such as L- and U-shaped FP resonators can be constructed in the surface-wave bandgap crystal because of the high-efficiency transmission through sharp corners.²⁶ This cannot be achieved using a PEC as the reflector.

Direct imaging of the surface plasmon near-fields on the FP open resonator was performed using a microwave near-field scanning system to directly verify this resonance condition. Fig. 3(c) shows the measured E_z field distributions of the seven resonance modes in both the transverse xy plane (1 mm above the FP open resonator) and the vertical xz plane (starting from 1 mm above the FP open resonator). As expected, the standing surface waves occur at each resonance peak in the near-field response spectrum of Fig. 3(b) due to the multiple spoof surface plasmon reflections at the entrance and end faces of the FP open resonator. One can easily see that the order (m) of the seven resonance modes is 1, 2, 3, 4, 5, 6, and 7 respectively. Interestingly, we observe a first-order mode (M_1) for this spoof surface plasmon FP open resonator, which is missed in all previous conventional FP resonators.⁵⁻⁷ We attribute this new emerged first-order FP mode to the tight confinement provided by the complete forbidden bandgap of the surrounding surface-wave bandgap crystal. The simulated field distributions of both the transverse and vertical planes of the FP resonators are also shown in Fig. 3(d) for comparison, which match well with the measured results shown in Fig. 3(c).

These FP resonance modes are standing surface waves along the finite line defect which exist whenever an integer of half the surface plasmon wavelength equals to the length of the finite line defect. Thus, we can write the resonance condition of the FP open resonator as follows: $K_{spp} \times l = m \times \pi - \varnothing$, where K_{spp} is the wavevector of the surface waves, $l = N \times d$ is the length of the FP open resonator (N is the

FIG. 2. (a) Calculated band structure of the surface-wave bandgap crystal. The yellow region represents the forbidden bandgap. (b) Measured transmission spectrum through the surface-wave bandgap crystal.

FIG. 3. (a) Experimental setup to measure the near-field response spectrum and near-field mode profiles of the Fabry-Perot open resonator which consists of seven defect pillars (red dots). Two antennas as the point source and probe are indicated by two red arrows. (b) Measured near-field response spectrum of the FP open resonator (black line). The inset shows the schematic of the open resonator. The yellow region indicates the forbidden surface-wave bandgap of the surrounding surface-wave bandgap crystal. (c) Observed and (d) simulated field patterns (E_z) of the seven corresponding resonance peaks (M_1 - M_7) in both the transverse and vertical planes above the top surface of the FP resonator.

number of the defect pillars), $\varnothing$ is the reflection phase of the entrance (or end) face of the FP open resonator, and m is an integer denoting the order of the resonance modes. Note that the end-face reflection phase shift at both terminations ($\varnothing$) can be approximately experimentally retrieved from the measured resonance frequencies and the dispersion relation of the line-defect waveguide.²⁶ For instance, for the second-order resonance mode ($m=2$) of the FP open resonator with defect pillar number $N=7$, its measured resonance frequency is 12.86 GHz, and then, we can get the wavevector (K_{spp}) from the dispersion relation that $K_{spp} = 0.4\pi/d$ and the total length of the resonator $l = N \times d$, where d is the periodicity of the line defect. Thus, we can approximately deduce that the reflection phase for the second-order resonance mode of the FP open resonator with defect pillar number $N=7$ is about $\varnothing = 0.2\pi$.

We further decrease the defect pillar numbers of the FP open resonator to $N=5$ [inset of Fig. 4(a)]. For a shorter finite line-defect length, we expect to have FP resonances that are spectrally farther apart in analogy to the larger mode spacing in a conventional shorter FP resonator. We use the same experimental setup (two short antennas as the point source and probe are indicated with black arrows) to measure its near-field response spectrum, as shown in Fig. 4(a), from which five resonance peaks with larger mode spacing can be observed. The corresponding measured near-field distributions (E_z) of the five resonance peaks (M_1 - M_5) are presented in Fig. 4(b). It is clear that the mode order is 1, 2, 3, 4, and 5 for the five resonance modes.

Compared with the longer FP open resonator in Fig. 3, several conclusions can be drawn from the measured near-

field response spectrum and mapped near-field mode profiles. First, the total numbers of FP resonance modes are decreased from seven to five, and two highest order FP modes (M_6 , M_7) disappear from the near-field response spectrum when the defect pillar numbers decrease from $N=7$ to $N=5$. That is because, in order to maintain the same mode order (m), decreasing defect numbers (N) must be accompanied by the increasing wavevector (K_{spp}) of propagating spoof surface plasmons. Thus, for the FP open resonator with defect number $N=5$, when the mode order is higher than five ($m \geq 6$), the wavevector (K_{spp}) will be beyond the edge of the first Brillouin zone of the spoof surface plasmon dispersion¹⁰ in an infinite line-defect waveguide, and thus, the propagation of spoof surface plasmons will be cutoff and the FP resonances disappear. Second, for the same order mode (for example, $m=1$), when the defect numbers decrease from $N=7$ to $N=5$, the resonance frequencies of the first-order mode (M_1) increase from

FIG. 4. (a) Measured near-field response spectrum of a Fabry-Perot open resonator consisting of five defect pillars. The inset shows the schematic of the open resonator. (b) Measured field patterns (E_z) of the five resonance modes (M_1 - M_5) in a transverse plane 1 mm above the top surface of the FP resonator.

FIG. 5. (a) Measured near-field response spectrum of a Fabry-Perot open resonator consisting of three defect pillars. The inset shows the schematic of the open resonator. (b) Measured field patterns (E_z) of the three resonance modes (M_1 - M_3) in a transverse plane 1 mm above the top surface of the FP resonator.

12.65 GHz to 12.75 GHz. This is because decreasing the defect numbers (N) shrinks the total length (l) of the FP open resonator, and the wavevector of spoof surface plasmons (K_{spp}) needs to be increased to meet the resonance condition of the fixed mode order ($m = 1$). Thus, the resonance frequencies of the FP resonator modes with the fixed mode order also increase, following the dispersion relation of spoof surface plasmons propagating along the line-defect waveguide in a surface-wave bandgap crystal.²⁶

When we continue to decrease the defect pillar numbers to $N = 3$, as shown in the inset of Fig. 5(a), we can only observe three resonance peaks in the measured near-field response spectrum. The measured near-field mode profiles corresponding to the three resonance peaks (M_1 - M_3) reveal that their mode orders are 1, 2, and 3, respectively. For completeness, we further decrease the defect number to $N = 1$, as shown in the inset of Fig. 6(a). It is obvious that we can only observe a single resonance peak in the measured near-field response spectrum. This single resonance peak corresponds to the first-order resonance mode (M_1), whose measured mode profile (E_z) is shown in Fig. 6(b).

Note that the first-order mode (M_1) always exists no matter how the number of the defect pillars changes. However, for the traditional plasmonic FP resonators,⁵⁻⁹ if we continue to decrease the resonator length, they will gradually reduce to small plasmonic particles with size much smaller to the light wavelength, and their resonance properties are mainly characterized by dipolar features. The emergence of the first-order FP plasmonic mode (M_1) mainly

FIG. 6. (a) Measured near-field response spectrum of a single point defect in a surface-wave bandgap crystal. The inset shows the schematic of the point defect. (b) Measured field pattern (E_z) of the single resonance modes (M_1) in a transverse plane 1 mm above the top surface of the point defect.

comes from the advantage of the combination of a photonic crystal and subwavelength nature of surface plasmons.

In conclusion, we have proposed and experimentally demonstrated that a finite line defect in surface-wave bandgap crystals works as a new configuration of spoof surface plasmon FP open resonators at the microwave frequencies. We also show that both the total numbers and resonance frequencies of the FP resonance modes can be conveniently modified by changing the defect pillar numbers of the open resonator rather than its complete geometry, simplifying the design of FP open resonators to only one degree of freedom. Moreover, we observe a first-order mode for this spoof surface plasmon FP open resonator, which is missed in all previous traditional FP resonators and plasmonic resonators, due to the forbidden bandgap provided by the surface-wave bandgap crystal. These results will be useful for future plasmonic resonator design that is important for integrated plasmonic circuits.

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