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Directive Emission Derived from A Meta-surface with Complete Bandgap of Surface Resonances

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Abstract: The complete bandgap of surface resonances on a metal plate perforated with a triangular array of air holes was theoretically and experimentally investigated. Parametric study of holes size implies that the triangular lattice is predominant to the formation of the complete bandgap. As a useful application, highly directive emission from a dipole antenna positioned near the meta-surface is observed at the lower band edge and at other frequencies inside the bandgap. It has a half power beamwidth of 5.6° in ***E***-plane and 6.2° in ***H***-plane, exhibiting a very high directivity.

Key words: metamaterials; surface resonance bandgap; directive emission
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具有表面波完全极化禁带的平面特异材料的定向辐射效应

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摘要: 从理论和实验上研究了镂有三角晶格小孔阵列的金属薄板表面波禁带行为,通过改变小孔直径以及其他几何参数,发现三角晶格是表面波完全极化禁带产生的原因。利用该表面波完全禁带实现了点源的定向辐射。通过测量放在该平板表面的偶极子天线辐射源的远场方向图,观测到在表面波完全禁带里面,远场方向图的 ***E*** 面和 ***H*** 面半高宽分别只有 5.6°和 6.2°。

关 键 词: 特异材料; 表面波完全极化禁带; 定向辐射

1 Introduction

Structured metal surfaces support electromagnetic surface modes bound to the metal/dielectric interface, giving rise to remarkable optical phenomena including extraordinary optical transmission (EOT) through subwavelength hole arrays[1-6]. These modes are called surface plasmon polaritons (SPPs)[7] at

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visible and near-infrared frequencies, and characterized by strongly enhanced local field at the interface. In the microwave regime, metals can be treated as plasmon-free perfect conductors. However, with the assistance of localized surface resonances, a structured perfect metal surface can support mimicking surface plasmons and design artificial ones with almost arbitrary dispersion in frequency and in space[8-10]. With these plasmon-like local resonances, there still exists EOT in terahertz[11] and microwave region[12].

Surface mode bandgap engineering is very crucial to light manipulation by plasmonic materials and metamaterials. It has been recently reported that a metal plate perforated with a triangular array of air holes possesses complete bandgap of surface resonances and presents beam collimation effect in a certain frequency range covering the bandgap[13]. As the complete surface resonances bandgap suppresses any surface resonances with nonzero in-plane wave vectors, it can be utilized to design directional antennas.

In this paper, we theoretically and experimentally investigate the microwave EOT through a thin aluminum plate perforated with a triangular array of air holes. Modal expansion method (MEM)[14-16] is employed to calculate the transmission spectra under plane wave incidence and extract the dispersion of surface resonances on the meta-surface. A complete bandgap is found at 10.20 ~ 10.94 GHz for all polarizations and all in-plane wave vectors. It is verified by parametric study of holes size that the triangular lattice is predominant to the formation of the complete bandgap. A dipole antenna positioned near the meta-surface radiates directionally at low band edge and other frequencies within the bandgap, which can be applied to realize a new kind of surface wave antenna with high directivity.

2 Model Description

As shown in Fig. 1(a), the sample is fabricated on an aluminum plate with a thickness of $t = 2$ mm and a lateral size of 1 000 mm × 1 000 mm. The lattice constant of the triangular array is $p = 30$ mm. The diameter of holes is $d = 15$ mm. The front surface of the sample plate and the irreducible Brillouin zone of the triangular lattice are schematically illustrated in Fig. 1(b) and Fig. 1(c).

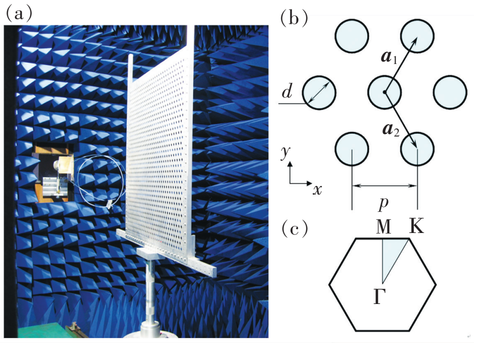

Fig. 1 Schematic of the model system. (a) A photo of the experimental setup. (b) The front surface of the sample plate. (c) The irreducible Brillouin zone of the triangular lattice.

Angle-dependent transmission spectra and radiation patterns are measured in microwave chamber with Agilent 8722ES network analyzer. The sample plate is on a rotary table which is controlled by computer with a finest angular resolution of 0.1°.

3 Complete Bandgap of Surface Resonances

Transmission spectra under different incident angles are calculated by MEM. Fig. 2 shows the dispersion of surface resonances extracted from transmission spectra by tracing the peak frequencies as a function of in-plane wave vector[1]. The even-mode surface resonances are marked by circular dots, while the odd-mode surface resonances are represented by gray dashed lines. It is noted that the even-mode surface resonances possess a bandgap at 10.20 ~ 11.52 GHz for TM polarization, which fully covers the TE polarization bandgap at 10.20 ~ 10.94 GHz. Thus the complete bandgap for all polarizations and all in-plane wave vectors has a width of 740 MHz, which is marked by the shadowed region in Fig. 2.

It can be seen from Fig. 2 that the width of the complete bandgap is determined by the TE polarization bandgap along ΓK direction. We take parametric study of holes size to get an insight into this part

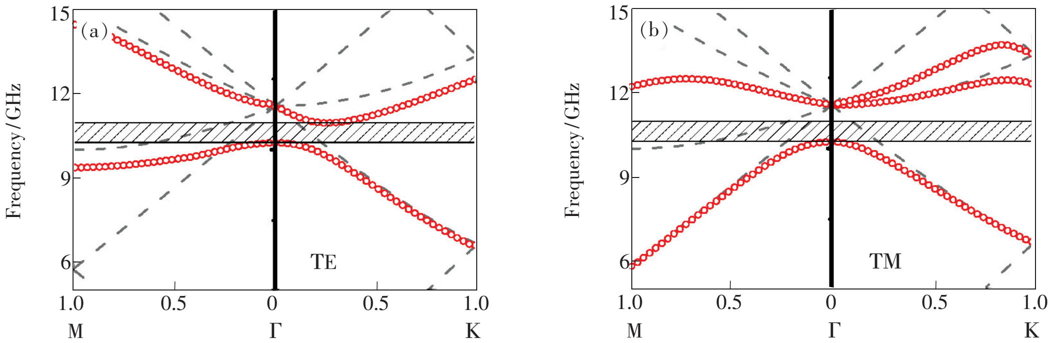

Fig. 2　Dispersion diagrams for TE(a) and TM(b) polarized surface resonances for the sample with a triangular array in even-mode (circular dots) and odd-mode (dashed lines). The complete bandgap is marked by the shadowed region.

of surface resonances dispersion. The diameter of holes d is varied from 11 mm to 21 mm at intervals of 2 mm. It is found that there always exists a complete bandgap below the Rayleigh frequency $f_R = (2/\sqrt{3}) \cdot c_0/p = 11.53$ GHz as shown in Fig. 3. As compared to the above studied case, $d = 15$ mm (see Fig. 3(c)), the bandgap is wider in frequency range for a larger size of air holes (see Figs. 3(d) ~ 3(f)).

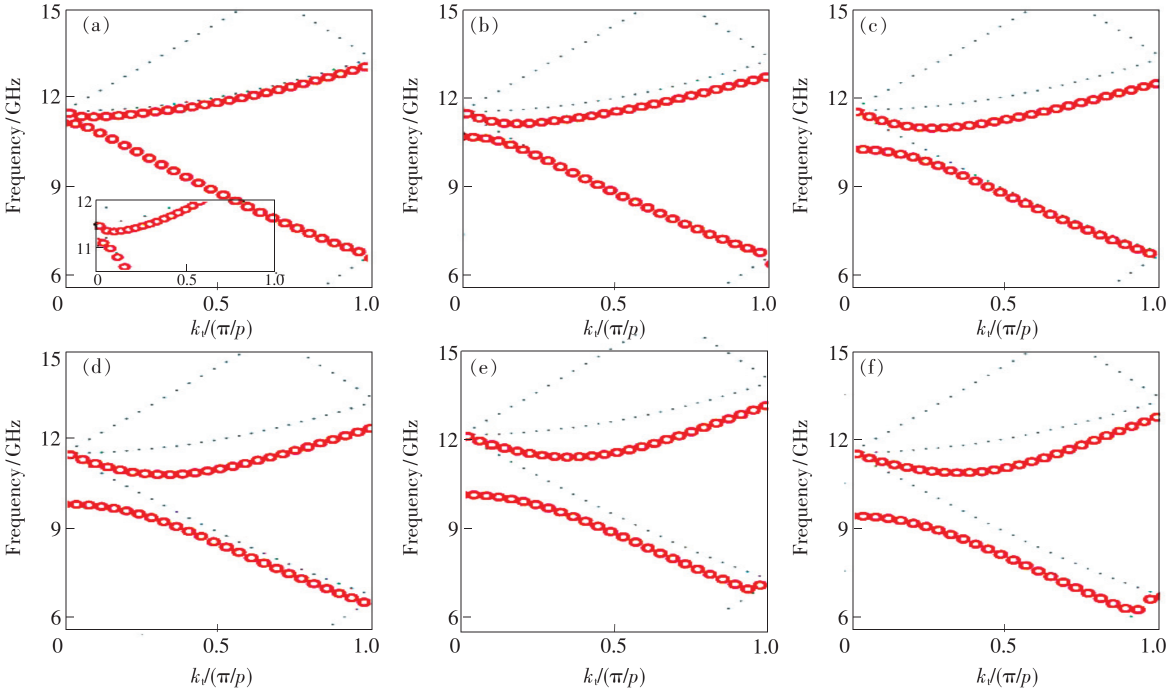

Fig. 3　Dispersion diagrams for TE polarized surface resonances along ΓK direction for different holes size. (a) $d = 11$ mm. (b) $d = 13$ mm. (c) $d = 15$ mm. (d) $d = 17$ mm. (e) $d = 19$ mm. (f) $d = 21$ mm.

4　Directive Emission from The Meta-surface

To demonstrate the directive emission from the meta-surface, we adopt a dipole antenna working at 10 GHz for the measurements. It is positioned along the x direction and 2 mm apart from the surface of perforated aluminum plate.

Directive emission is attainable within the frequency range of 10.20 ~ 10.94 GHz inside the bandgap. The measured half power bandwidths are 5.6° in ***E***-plane and 6.2° in ***H***-plane with an optimal return loss about −10 dB at the lower band edge 10.20 GHz. Blue and green circular dots in Fig. 4 present the measured polar charts at 10.20 GHz. For verification, we perform FDTD simulations to calculate the radiation patterns from a dipole close to a model plate with a lateral size of 300 mm × 260 mm.

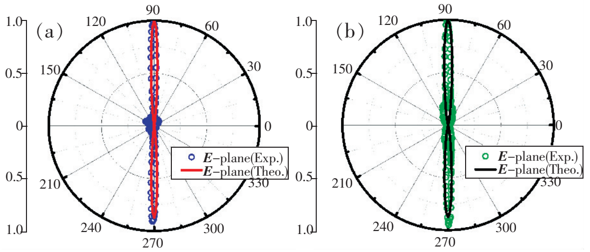

Fig. 4 The measured (circular dots) and calculated (solid line) radiation patterns at 10.20 GHz from a dipole antenna positioned along the *x* direction and 2 mm apart from the meta-surface in ***E***-plane (a) and ***H***-plane (b)

The calculated half power bandwidths are 6.8° in ***E***-plane and 7.1° in ***H***-plane, shown as red and black lines in Fig. 4, which coincide with the measurements.

5 Conclusion

In summary, we find that a complete bandgap of surface resonances exists on a meta-surface arranged with a triangular array of air holes. It is proved that the triangular lattice is predominant to the formation of the complete bandgap, and the bandgap always exists during the variation of holes size. Directive emission from a dipole antenna positioned near the meta-surface, with half power beamwidth of 5.6° in ***E***-plane and 6.2° in ***H***-plane, is observed in the complete bandgap. The findings are helpful in realizing beam collimator and high directive antennas with ultra thin structure.

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