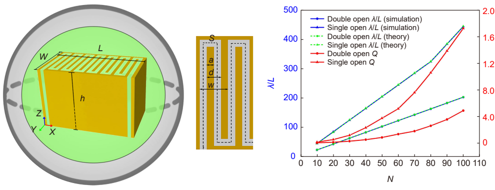
Opto-Electronic Engineering
光电工程

Article
2022 年, 第 49 卷, 第 9 期

DOI: 10.12086/oee.2022.220037

空间填充型曲线的人工局域表面等离激元共振特性研究



乔晓晨[1]，史　坦[1]，宋世超[1]，
傅　涛[2]，李向平[1]，邓子岚[1*]

[1] 暨南大学光子技术研究院，广东省光纤传感与
通信重点实验室，广东 广州 510632；
[2] 桂林电子科技大学信息与通信学院，广西精密导航技术与
应用重点实验室，广西 桂林 541004

摘要：本文提出了一种基于空间填充曲线的超构表面结构，利用理论分析、数值仿真的方法研究了该超构表面的近场电磁特性，实现了高度局域及高品质因子 (Q-factor) 的多阶人工局域表面等离激元共振 (spoof plasmon resonances)。我们发现采用不同结构形状和尺寸的空间填充曲线均可产生共振频率规则分布的多阶谐振模式，通过调整结构的等效波导长度，可同时获得高的谐振波长/结构尺寸压缩比与高品质因子。空间填充曲线所支持的人工局域表面等离激元由磁偶极子与电偶极子模式交替支持；其余参数不变的情况下改变空间填充曲线的分布形式，结构所支持的表面等离激元的谐振特性不受形状曲折的影响，而只与等效波导总长度有关。此外，近场模式的强度分布随着空气波导的走向而改变，可根据实际需求对结构进行特定排布。本文的研究结果对设计基于空间填充曲线的小型化高品质因子电磁谐振器件具有重要的指导意义。

关键词：超构表面；局域表面等离激元；场共振增强；等离激元波导

中图分类号：TN252；TB383　　**文献标志码：**A

乔晓晨，史坦，宋世超，等. 空间填充型曲线的人工局域表面等离激元共振特性研究 [J]. 光电工程，2022，**49**(9): 220037
Qiao X C, Shi T, Song S C, et al. Highly confined localized spoof plasmon resonance characteristics on space-filling curvilinear meta-structures[J]. *Opto-Electron Eng*, 2022, **49**(9): 220037

Highly confined localized spoof plasmon resonance characteristics on space-filling curvilinear meta-structures

Qiao Xiaochen[1], Shi Tan[1], Song Shichao[1], Fu Tao[2], Li Xiangping[1], Deng Zilan[1*]

[1] Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonic Technology, Jinan University, Guangzhou, Guangdong 510632, China;
[2] Guangxi Key Laboratory of Precision Navigation Technology and Application, Institute of Information and Communication, Guilin University of Electronic Technology, Guilin, Guangxi 541004, China

---

收稿日期：2022-04-05；收到修改稿日期：2022-06-07
基金项目：国家自然科学基金资助项目 (62075084)；广东省自然科学基金资助项目 (2020A1515010615)；中央高校基本科研业务费专项资金；广州市基础与应用基础研究项目 (202102020566)

*通信作者：邓子岚，zilandeng@jnu.edu.cn。

Abstract: With the advent of the 5G communication era, much attention has been paid to manipulate electromagnetic waves at subwavelength scale. In this paper, we propose comb-shaped meta-structures based on space-filling curves, and use theoretical analysis and numerical simulation method to study the near-field electromagnetic properties of these meta-surfaces. Finally, the effective excitation of all order eigenmodes of spoof localized surface plasmon resonance can be realized in these meta-structures. Through adjusting the structure period to change the effective length of the air waveguide, high compression ratio between resonant wavelength and device size, and high Q-factor can be simultaneously achieved. Moreover, spoof localized surface plasmons excited by space-filling structures are alternately supported by magnetic dipole and electric dipole modes. As a consequence, changing the distribution form of the space-filling curve with the remaining parameters unchanged, the resonant characteristics of the surface plasmon supported by the structure are not affected by the shape tortuosity, but are only related to the total length of the equivalent waveguide. Thus, the space-filling curvilinear structure can be freely designed. We believe that, our results have great potential in designing the high Q-factor miniaturized electromagnetic resonator devices based on spacing-filling curvilinear meta-structure.

Keywords: meta-surface; localized surface plasmon; field resonance enhancement; plasmonic waveguides

1 引 言

信息数据的传输是 5G 通信时代的关键，为了实现每秒数十 GB 的数据吞吐量并满足移动数据服务和新型应用的需求，人们将工作频段拓宽到之前未被充分利用的毫米波频段。但是传统微波电路系统面临着如器件小型化和电磁匹配等问题。传统微波传输线的电磁波主要分布在介质或周围空气中，在小型微波集成电路中相邻传输线之间存在较强耦合，从而对系统整体性能会造成一定影响，因此寻找一种能在亚波长尺度上操纵电磁波的结构尤为重要。

表面等离激元 (Surface plasmon polariton, SPP) 是一种亚波长尺度下局域电磁波的表面波模式[1-3]，它主要分为两类，一类是沿金属表面传播的传播型表面等离激元 (propagating surface plasmon polariton, PSPP)[4-5]，另一类是由孤立金属纳米结构支持的局域表面等离激元共振 (local surface plasmon resonance, LSPR)[6-7]。表面等离激元在特定频段范围内所具有的场束缚和场增强特性在诸多领域均有巨大的应用潜力[8-10]，例如传播型表面等离激元可实现电路的集成化[11-12]、光通信[13-14] 和光开关[15-16] 等，局域表面等离激元的局域场增强效应可用于生物传感[17]、近场光学[18-19]、天线[20-21]、光伏[22-23]、超构表面[24-25] 等。表面等离激元最早可以追溯到 1902 年在金属光栅中发现的异常反射[26]，由于支持表面等离激元模式的贵金属材料在光频段吸收损耗较高，为解决这一损耗问题，研究者们在微波频段通过精心设计完美电导体 (perfect electric conductor, PEC) 亚波长孔洞结构，构建了一种类似光学 SPP 的表面波，由此提出人工表面等离激元 (spoof surface plasmon) 的概念[27-29]。人工表面等离激元用结构谐振代替光子-电子耦合谐振，其谐振频率可拓展至太赫兹波段甚至微波频段，且在微波频段金属损耗较低，可支持较强的场束缚能力[30-31]。早期的人工表面等离激元超构材料为三维立体结构，存在尺寸大、不易加工等问题，因此研究人员提出并设计了平面型超薄人工局域表面等离激元谐振结构[32-36]，这种可通过普通工艺印刷在介质基底上的平面结构，解决了传统结构体积庞大的问题，可高效利用传统集成电路的加工工艺。

结构尺寸压缩比 (谐振波长/结构尺寸—λ/L) 和品质因子 (Q-factor) 是电磁谐振结构的两个重要参数，但这两者往往存在制约关系。现有电磁共振器中，高 Q 因子的共振模式往往需要在高阶模式中获得，因为高阶模式具有反相位分布特征，辐射损耗较小。而高阶模式往往具有低的结构尺寸压缩比 (谐振频率更高，谐振波长/结构尺寸更小)。为了同时获得具有高结构尺寸压缩比与高 Q 因子的谐振器件，本文研究了一种基于空间填充曲线的超薄超构表面，利用人工局域表面等离激元谐振的特性设计了一种深度亚波长金属谐振结构，通过理论分析与模拟仿真对结构近场的人工局域表面等离激元做了系统研究。该空间填充曲线是越低阶的模式，则与自由空间光的波矢匹配程度越小，与外界耦合更小，Q 因子则越高，因此能有效克服结构尺寸压缩比与品质因子之间的制约关系。相比于已报道的齿轮状结构及其相关变形结构[37]，空

间填充曲线结构能够同时实现高结构尺寸压缩比与高 Q 因子的人工表面等离激元共振，且其共振频谱呈规则等距分布，不随空间曲线形态变化等优势，可为电磁共振器件提供更加优异稳定的高阶谐振性能。

2 理论分析与仿真模拟

2.1 空间填充曲线结构的共振模型

我们通过有限元法对梳型空间填充金属曲线结构进行二维模拟仿真，仿真结构示意图如图 1(a) 所示。将空间填充金属 (模拟中设置为完美电导体) 曲线结构放置在空气介质 (介电常数 $\varepsilon = 1$) 的背景空间中，如图 1(a) 中的绿色区域所示，外层浅灰色为完美匹配层，模型边界采用散射边界。金属曲线在空间中卷曲填充，形成卷曲状空气波导，空气波导的有效长度为图中所示虚线的总长度，记为 S，金属宽度 $a = 2.5$ mm，卷曲周期 $w = 2d = 10$ mm，金属在周期中的占空比为 $a/d = 0.5$。结构的周期数为 N，长度为 L，宽度为 W。我们首先采用二维模型计算梳型空间填充结构 (Z 方向厚度视为无穷 $h \to \infty$)。通过整合结构封闭区域的坡印廷矢量积分除以面积计算的散射截面 (scattering cross-section, SCS)、结构表面的电、磁场分布以及各阶本征模的偶极子模式来研究结构的人工局域表面等离激元特性。

空间填充金属曲线在近场激发下，表面等离激元在结构的空气波导之间弹跳，集体震荡形成类法布里-珀罗 (Fabry–Pérot, FP) 谐振表面模，谐振频率由空气波导的有效长度 S 决定。对于双开口梳状空间填充金属曲线结构如图 1(b)，忽略金属宽度的情况下，其与结构参数之间的关系如下：

$$S = 2NW + Nw\,, \tag{1}$$

其中：N 为结构的周期数，W 为结构的宽度，w 为结构的卷曲周期。

根据 FP 的共振条件：

$$\lambda/2 + M\lambda = S, (M = 0, 1, 2, ...)\,, \tag{2}$$

其中：λ为共振波长，M 为本征模式阶数。

因此满足以下谐振频率公式时可产生共振：

$$k_0 L = \frac{\pi(2M+1)L}{S}, (M = 0, 1, 2, ...)\,, \tag{3}$$

其中：k_0为波矢，$k_0 = 2\pi/\lambda$。为了讨论方便，我们记$k_0 L$为归一化谐振频率，描述结构尺寸与共振波长之间的比例系数，L 为结构的长度。

对于单开口梳状空间填充金属曲线结构如图 1(c)，

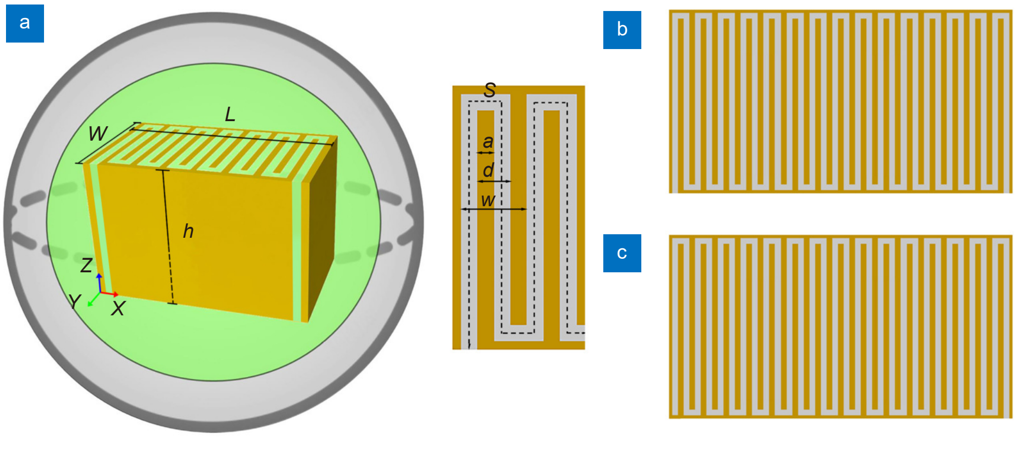


图 1　梳型空间填充曲线结构示意图。

(a) 梳型空间填充曲线结构的二维物理仿真示意图，卷曲结构的周期 $w = 10$ mm，金属宽度 $a = 2.5$ mm，结构的宽度为 $W = 7.5$ cm，长度为 L，金属结构填充形成空气波导 (灰色区域)，其有效长度为 S，金属在周期中的占空比为 0.5；(b) 双开口梳型空间填充曲线结构；(c) 单开口梳型空间填充曲线结构

Fig. 1　The schematic diagram of the structure of the comb-shaped space-filling curve.

(a) The schematic diagram of the comb-shaped space-filled meta-structure and the simulation domain. The period w and duty cycle of the comb-shaped space-filling metallic curve structure are 10 mm and 0.5, respectively. The metal wire width a is 2.5 mm, half cycle width d is 5 mm, the total length of the structure is L, the width of the structure is W= 7.5 cm, the metal structure fills the air waveguide forming the gray part, and its effective length is S; (b) The schematic of double-open comb-shaped space-filling metallic curve structure; (c) The schematic of single-open comb-shaped space-filling metallic curve structure

空气波导的一端被 PEC 截止，形成表面模的反射，有效长度变为 2S，则其谐振频率为

$$k_0 L = \frac{\pi(2M+1)L}{2S}, (M = 0, 1, 2, ...) . \qquad (4)$$

2.2 表面等离激元谐振特性随空间填充曲线结构尺寸的变化规律

利用入射平面波对不同周期数 N 的双开口和单开口梳状空间填充金属曲线结构分别进行激发并仿真计算，图 2(a~b) 分别为两种结构表面基模的磁场 ($\boldsymbol{H}_Z$) 分布情况，图 2(c) 为不同周期数结构基模下的结构尺寸压缩比和 Q 因子与空气波导有效长度 S 之间的关系，从图中蓝色曲线和绿色曲线可知，两种结构仿真模拟所得的结构尺寸压缩比与式 (3)、式 (4) 理论解析分析所推导的结果一致。同时单开口梳型结构由于反射作用使得空气波导的有效长度变为 2S，进一步提高了结构尺寸压缩比。从红色曲线可以看出，两种结构的 Q 因子随着周期数的增加而迅速增长，其中单开口梳型结构的 Q 因子可达 1.7×10^5，增长速度明显大于双开口结构，已有的相关研究报道在结构尺寸压缩比为 20 的结构中可产生 104.8 的 Q 因子[38]，与之相比，空间填充曲线结构对深度亚波长谐振结构的 Q 因子具有很大的提升。以上结果表明通过改变周期数的方式来改变结构空气波导的有效长度 S 可以调节该超构表面的结构尺寸压缩比，并有效提高 Q 因子。需要注意的是，我们目前的计算过程中将金属考虑为 PEC，忽略了其欧姆损耗。在实际结构中，金属的欧姆损耗将导致 Q 因子与周期性 N 的正相关出现收敛趋势，使得 Q 因子与结构周期数存在制约关系。

2.3 表面等离激元谐振随空间填充曲线结构分布的变化规律

在优化梳状空间填充金属曲线结构参数的仿真模拟后，选择周期数 $N = 15$ 的双开口梳型空间填充金属曲线结构对高阶等离激元共振模式进行具体分析，该参数下结构长度 $L = 15$ cm，空气波导的有效长度 $S = 2.4$ m。由于 TE 偏振 (电场 $\boldsymbol{E}$ 指向 X 方向) 入射光仅能激发奇数阶模式，而 TM 偏振 (电场 $\boldsymbol{E}$ 指向 Y 方向) 入射光对奇数、偶数阶模式均能激发，因此，我们采用 TM 偏振入射平面波对结构进行背景场激励。图 3(a) 为结构在背景场激励下 M_0~M_9 本征模的散射截面，可见各阶本征模的谐振频率为等间距分布且满足前文推导的计算公式 (3)，纵坐标散射截面随着本征模阶数的增加逐渐减小，图 3(b) 为结构 M_0~M_4 阶本征模的磁场图及其对应的多极子模式，从磁场分布图中可以看出梳型空间填充曲线结构的共振表面模满足典型的驻波模式 (结构表面上红蓝交替的磁场出现相位相反的振幅对称分布)，为人工局域表面等离激元共振来自类 FP 谐振提供了实证依据；极子模式图中的 MD、ED、MQ、EQ 分别表示磁偶极子、电偶

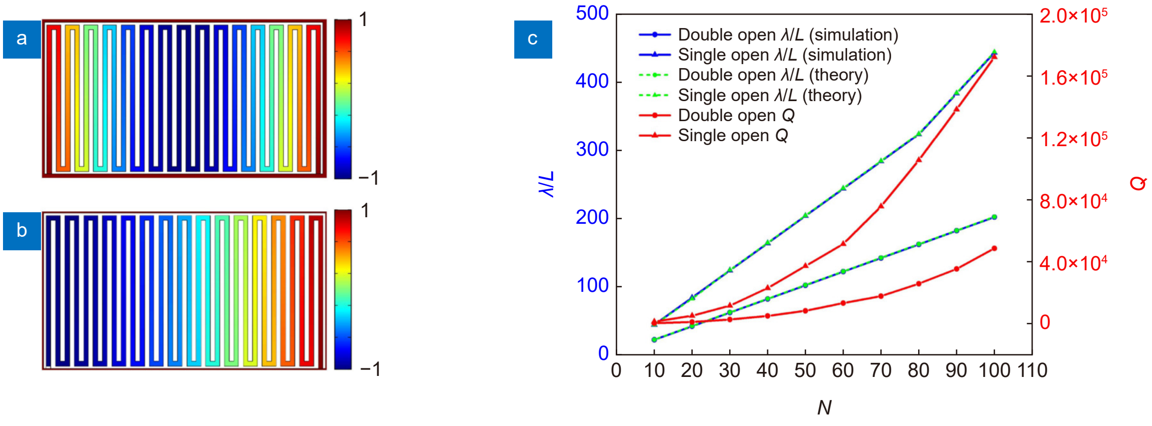


图 2　不同周期数的单开口和双开口梳型结构的二维模拟仿真。

(a) 双开口梳状空间填充金属曲线结构的基模磁场分布图；(b) 单开口梳状空间填充金属曲线结构的基模磁场分布图；(c) 梳型双开口和梳型单开口结构的结构尺寸压缩比的理论与仿真值以及 Q 因子随着周期数 N 的变化情况

Fig. 2　2D simulation of single-opening and double-opening comb structures with different number of periods.

(a) The magnetic field distribution of fundamental mode in the double-opening comb-shaped space-filled meta-structure. (b) The magnetic field distribution of fundamental mode in the single-opening comb-shaped space-filled meta-structure; (c) The theoretical and simulated structure compression ratios, and the Q factors of the double-opening and single-opening comb-shaped space-filled meta-structures as functions of period number N, respectively

极子、磁四极子、电四极子，从图中可以看出各阶本征模由磁偶极子模式和电偶极子模式交替支持，奇数阶本征模由磁偶极子主导，偶数阶本征模由电偶极子主导。

我们进一步对不同形状的空间填充曲线结构的局域表面激元共振特性进行了研究。图 4(a~c) 为希尔伯特曲线结构、螺旋结构、梳型螺旋组合结构等金属空间填充曲线以及其对应的 M_0~M_4 阶本征模的磁场 ($\boldsymbol{H_Z}$) 分布图，可以看出结构表面的磁场强度随着空气波导的排布而改变，即空间填充结构的局域表面等离激元的谐振不受结构曲折形状的影响，因而在结构上具有极大的设计自由度。图 4(d) 为三种结构各阶本征模的散射截面与归一化谐振频率的关系，其谐振频率等间隔出现且依然满足由 FP 谐振推算的共振条件。结果表明，空间填充曲线金属结构的谐振只与结构空气波导的有效长度 S 相关，不受结构曲折形状的影响，结构的磁场分布和谐振频率均可通过结构空气波导的排布进行调控。

2.4 超薄空间填充曲线结构的三维仿真模拟

对双开口梳型空间填充曲线结构进行三维结构模拟仿真，如图 5(a) 所示为超薄空间三维结构示意图，其具体结构参数为：周期 $w = 2d = 10$ mm，金属宽度 $a = 2.5$ mm，占空比为 $a/d = 0.5$，结构长度 $L = 15$ cm，结构宽度 $W = 7.5$ cm，高度 $h = 0.05$ mm，周期数 $N = 15$。三维仿真采用传播方向为 Z 轴，电场 $\boldsymbol{E}$ 指向 Y

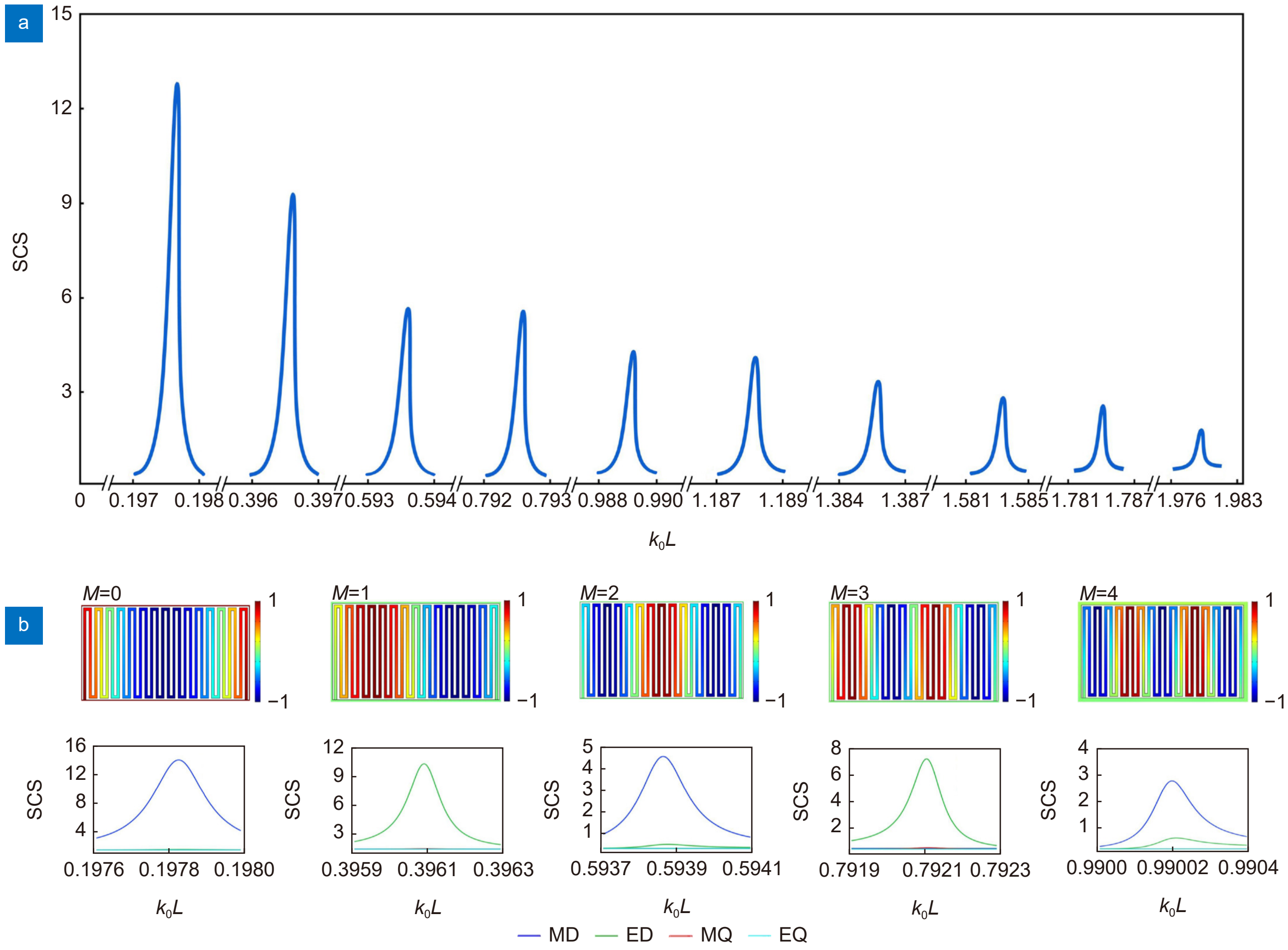


图 3　双开口梳型结构的高阶本征模计算。

(a) 双开口梳状空间填充金属曲线结构 M_0~M_9 本征模的散射截面；

(b) 双开口梳状空间填充金属曲线结构 M_0~M_4 阶本征模的磁场分布图及其对应的极子模式

Fig. 3　Higher-order eigenmode calculations for double-open comb structures.

(a) The scattering cross-section of the eigenmodes (M_0~M_9) of the double-opening space-filling metal curve structure;

(b) The magnetic field distributions of the M_0~M_4 order eigenmodes of the double-opening-space-filling metal curve structure in the Z direction and the pole mode of each order corresponding to the eigenmode

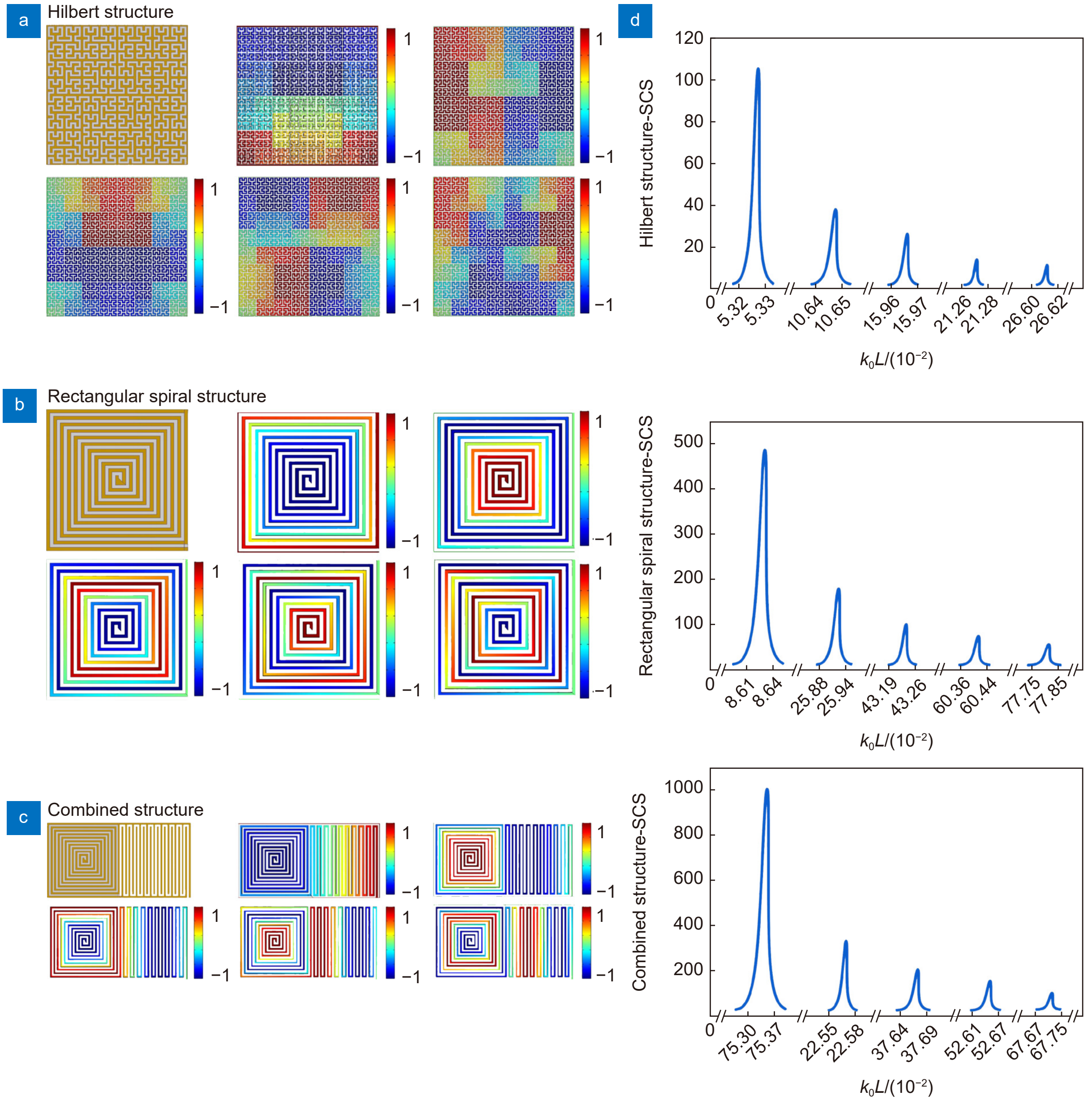


图 4　多种类型的空间填充曲线结构的人工局域表面等离激元共振特性。

(a~c) 希尔伯特曲线 (a)、矩形螺旋曲线 (b) 和组合曲线 (c) 填充结构示意图以及对应的 M_0~M_4 阶本征模的磁场分布；(d) 三种结构各阶本征模的散射截面与归一化频率的关系

Fig. 4　2D simulation of various types of space-filling curvilinear structures.

(a) The schematic diagram of Hilbert-type space-filling meta-structure and the magnetic field distributions at different eigenmode orders (M_0~M_4);

(b) The schematic diagram of rectangular spiral structure and the magnetic field distributions at different eigenmode orders (M_0~M_4);

(c) The schematic diagram of combined structure and the magnetic field distributions at different eigenmode orders(M_0~M_4);

(d) The scattering cross-section of the corresponding eigenmodes (M_0~M_4) of the preceding meta-structures

轴的 TM 偏振入射平面波对结构进行背景场激励。图 5(b) 为结构仿真 M_0~M_3 本征模电场的 X~Z 剖面图，从图中可以看出能量被束缚在结构的表面，符合人工局域表面等离激元的特性，具有较强的场束缚和场增强能力。

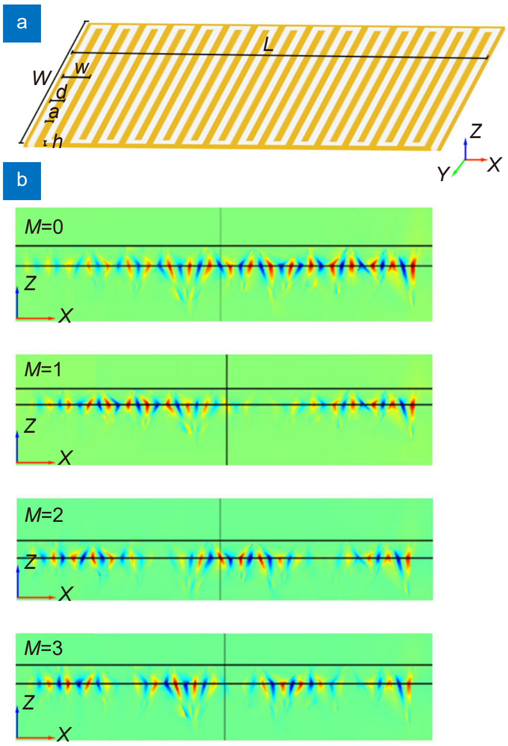


图 5　双开口梳型结构的三维模拟仿真。
(a) 周期数为 15 的双开口梳型空间填充金属曲线三维结构示意图；(b) 双开口梳型三维仿真 M_0~M_3 本征模的电场在 X~Z 平面的分布图

Fig. 5　3D simulation of a double-opening comb structure.
(a) The schematic diagram of the three-dimensional double-opening comb-shaped space-filling metal curvilinear structure with a period number of 15; (b)The electric field distributions on X~Z section of the three-dimensional simulated eigenmodes of the double-opening comb-shaped space-filled meta-structure

3 结　论

本文提出了一种利用空间填充金属曲线结构构造人工局域表面等离激元的方案，研究了各种几何参数对其谐振特性的影响，同时在该结构中实现了通过选择开口模式和调节周期数 N 来控制其结构尺寸压缩比及 Q 因子大小。我们通过对特定尺寸的双开口梳型空间填充金属曲线结构进行详尽的仿真计算来分析结构可能存在的各阶本征模的场分布以及所支持的多极子模式，发现在梳型双开口结构中各阶本征的极子模式由磁偶极子和电偶极子交替主导。而且，改变结构中空气波导的排布可以改变局域表面等离激元的谐振峰位。三维超薄结构的仿真研究也表明了结构具有良好的场束缚能力，符合人工表面等离激元的电磁特性。

本文所提出的空间填充曲线超构表面结构可实现较高的 Q 因子，同时可根据不同的功能需求设计出满足工作在结构特定位置和特定频段的电磁谐振参数，在小型集成化电路设计应用中具有广阔的应用前景。此外，本文的研究思路也为具有高 Q 因子的小型电磁谐振器设计方案提供了参考，以便为小型集成化电路系统提供性能更加优异稳定的电子器件。

参考文献

[1] Ritchie R H. Plasma losses by fast electrons in thin films[J]. *Phys Rev A*, 1957, **106**(5): 874−881.

[2] Barnes W L, Dereux A, Ebbesen T W. Surface plasmon subwavelength optics[J]. *Nature*, 2003, **424**(6950): 824−830.

[3] Fang Z Y, Lu Y W, Fan L R, et al. Surface plasmon polariton enhancement in silver nanowire –nanoantenna structure[J]. *Plasmonics*, 2010, **5**(1): 57−62.

[4] Otto A. Excitation of nonradiative surface plasma waves in silver by the method of frustrated total reflection[J]. *Z Physik*, 1968, **216**(4): 398−410.

[5] Andrew P, Barnes W L. Energy transfer across a metal film mediated by surface plasmon polaritons[J]. *Science*, 2004, **306**(5698): 1002−1005.

[6] Faraday M X. The Bakerian Lecture. —Experimental relations of gold (and other metals) to light[J]. *Philos Trans R Soc Lond*, 1857, **147**: 145−181.

[7] Huidobro P A, Shen X P, Cuerda J, et al. Magnetic localized surface plasmons[J]. *Phys Rev X*, 2014, **4**(2): 021003.

[8] Pors A, Moreno E, Martin-Moreno L, et al. Localized spoof plasmons arise while texturing closed surfaces[J]. *Phys Rev Lett*, 2012, **108**(22): 223905.

[9] Viphavakit C, Boonruang S, Themistos C, et al. Surface plasmon resonance-enhanced light interaction in an integrated ormocomp nanowire[J]. *Opt Quant Electron*, 2016, **48**(5): 291.

[10] Li G H, Chen X S, Huang L J, et al. The localized near-field enhancement of metallic periodic bowtie structure: an oscillating dipoles picture[J]. *Phys B Condens Matter*, 2012, **407**(12): 2223−2228.

[11] Polman A, Atwater H A. Photonic design principles for ultrahigh-efficiency photovoltaics[J]. *Nat Mater*, 2012, **11**(3): 174−177.

[12] Zhang H C, Fan Y F, Guo J, et al. Second-harmonic generation of spoof surface plasmon polaritons using nonlinear plasmonic metamaterials[J]. *ACS Photonics*, 2016, **3**(1): 139−146.

[13] Zhang H C, Zhang L P, He P H, et al. A plasmonic route for the integrated wireless communication of subdiffraction-limited signals[J]. *Light Sci Appl*, 2020, **9**: 113.

[14] Zhang H C, Liu S, Shen X P, et al. Broadband amplification of spoof surface plasmon polaritons at microwave frequencies[J].

Laser Photonics Rev, 2015, **9**(1): 83−90.

[15] Krasavin A V, Zheludev N I. Active plasmonics: controlling signals in Au/Ga waveguide using nanoscale structural transformations[J]. *Appl Phys Lett*, 2004, **84**(8): 1416−1418.

[16] Pacifici D, Lezec H J, Atwater H A. All-optical modulation by plasmonic excitation of CdSe quantum dots[J]. *Nat Photonics*, 2007, **1**(7): 402−406.

[17] Wilson W D. Analyzing biomolecular interactions[J]. *Science*, 2002, **295**(5562): 2103−2105.

[18] Novotny L, Hecht B. *Principles of Nano-Optics*[M]. Cambridge: Cambridge University Press, 2012.

[19] Wang S, Deng Z L, Wang Y J, et al. Arbitrary polarization conversion dichroism metasurfaces for all-in-one full Poincaré sphere polarizers[J]. *Light Sci Appl*, 2021, **10**(1): 24.

[20] Yu N F, Cubukcu E, Diehl L, et al. Bowtie plasmonic quantum cascade laser antenna[J]. *Opt Express*, 2007, **15**(20): 13272−13281.

[21] Schnell M, García-Etxarri A, Huber A J, et al. Controlling the near-field oscillations of loaded plasmonic nanoantennas[J]. *Nat Photonics*, 2009, **3**(5): 287−291.

[22] Atwater H A, Polman A. Plasmonics for improved photovoltaic devices[J]. *Nat Mater*, 2010, **9**(3): 205−213.

[23] Heidel T D, Mapel J K, Singh M, et al. Surface plasmon polariton mediated energy transfer in organic photovoltaic devices[J]. *Appl Phys Lett*, 2007, **91**(9): 093506.

[24] Fang C Z, Yang Q Y, Yuan Q C, et al. High-*Q* resonances governed by the quasi-bound states in the continuum in all-dielectric metasurfaces[J]. *Opto-Electron Adv*, 2021, **4**(6): 200030.

[25] Zhang Y B, Liu H, Cheng H, et al. Multidimensional manipulation of wave fields based on artificial microstructures[J]. *Opto-Electron Adv*, 2020, **3**(11): 200002.

[26] Wood R W. XLII. On a remarkable case of uneven distribution of light in a diffraction grating spectrum[J]. *Lond Edinburgh Dublin Philos Mag J Sci*, 1902, **4**(21): 396−402.

[27] Pendry J B, Martín-Moreno L, Garcia-Vidal F J. Mimicking surface plasmons with structured surfaces[J]. *Science*, 2004, **305**(5685): 847−848.

[28] Hibbins A P, Evans B R, Sambles J R. Experimental verification of designer surface plasmons[J]. *Science*, 2005, **308**(5722): 670−672.

[29] Williams C R, Andrews S R, Maier S A, et al. Highly confined guiding of terahertz surface plasmon polaritons on structured metal surfaces[J]. *Nat Photonics*, 2008, **2**(3): 175−179.

[30] Luo Y, Chu C H, Vyas S, et al. Varifocal metalens for optical sectioning fluorescence microscopy[J]. *Nano Lett*, 2021, **21**(12): 5133−5142.

[31] Cai X D, Tang R, Zhou H Y, et al. Dynamically controlling terahertz wavefronts with cascaded metasurfaces[J]. *Adv Photon*, 2021, **3**(3): 036003.

[32] Shen X P, Cui T J, Martin-Cano D, et al. Conformal surface plasmons propagating on ultrathin and flexible films[J]. *Proc Natl Acad Sci USA*, 2013, **110**(1): 40−45.

[33] Liao Z, Luo Y, Fernández-Domínguez A I, et al. High-order localized spoof surface plasmon resonances and experimental verifications[J]. *Sci Rep*, 2015, **5**: 9590.

[34] Liao Z, Pan B C, Shen X P, et al. Multiple Fano resonances in spoof localized surface plasmons[J]. *Opt Express*, 2014, **22**(13): 15710−15717.

[35] Shi T, Deng Z L, Tu Q A, et al. Displacement-mediated bound states in the continuum in all-dielectric superlattice metasurfaces[J]. *PhotoniX*, 2021, **2**: 7.

[36] Deng Z L, Shi T, Krasnok A, et al. Observation of localized magnetic plasmon skyrmions[J]. *Nat Commun*, 2022, **13**(1): 8.

[37] Gao Z, Gao F, Xu H Y, et al. Localized spoof surface plasmons in textured open metal surfaces[J]. *Opt Lett*, 2016, **41**(10): 2181−2184.

[38] Zhang X R, Cui T J. Deep-subwavelength and high-Q trapped mode induced by symmetry-broken in toroidal plasmonic resonator[J]. *IEEE Trans Antenn Propag*, 2021, **69**(4): 2122−2129.

作者简介

乔晓晨 (1996-)，女，硕士研究生，主要从事电磁超构材料、微纳加工等领域的研究。

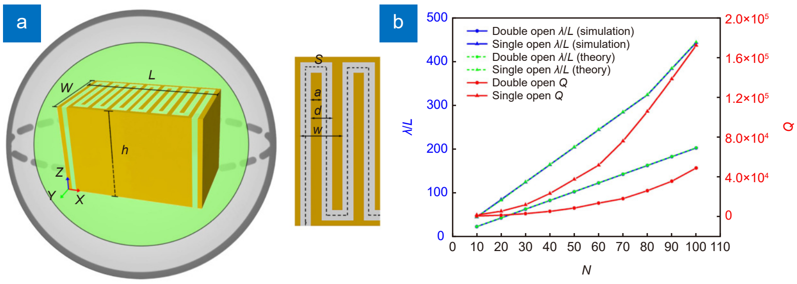
E-mail: xcqiao@stu2019.jnu.edu.cn

【通信作者】邓子岚 (1986-)，男，博士，教授，主要从事微纳光子学、电磁超构材料、新型光场调控等领域的研究。

E-mail: zilandeng@jnu.edu.cn

Highly confined localized spoof plasmon resonance characteristics on space-filling curvilinear meta-structures

Qiao Xiaochen[1], Shi Tan[1], Song Shichao[1], Fu Tao[2], Li Xiangping[1], Deng Zilan[1*]



(a) The schematic diagram of the structure of the comb-shaped space-filling curve; (b) The theoretical and simulated structure compression ratios, and the Q factors of the double-opening and single-opening comb-shaped space-filled meta-structures as functions of period number *N*, respectively.

Overview: With the advent of the 5G communication era, much attention has been paid to free manipulate electromagnetic waves at a subwavelength scale. Meta-surface with subwavelength structural dimensions have shown broad prospects in the field of microelectronic components due to their powerful electromagnetic control capabilities. In this paper, a subwavelength comb-shaped space-filling meta-surface is designed by using metal curves according to the resonator principle. A series of studies on spoof localized surface plasmon resonance characteristics are carried out on this basis. Theoretical analysis and calculation are carried out according to the structural characteristics. Compared with the traditional meta-surface supporting spoof localized surface plasmons, this curved arrangement of continuous metals will form an air waveguide similar to a resonant cavity, allowing for larger waveguide lengths at smaller dimensions, resulting in greatly reduced working frequency band. Under the excitation of the incident electromagnetic wave, spoof localized surface plasmon like Fabry-Perot resonance will be generated. The resonance frequency of the meta-surface can be calculated from the resonance conditions. Using the finite element method to simulate the 2D comb structure with different periods, it is found that the Q-factor of 1.7×10^5 can be obtained when the structure compression ratio (λ/L) is 444 by adjusting the structure period. In the study of the higher-order eigenmodes of the comb-shaped space-filled meta-structure, it was found that the spoof localized surface plasmons excited by space-filling structures are alternately supported by magnetic and electric multipoles modes, and the scattering cross-section of the eigenmodes of each order are presented at equally spaced frequencies. By changing the distribution type of the space-filling structure, the supported surface plasmon resonance properties are not affected by the arbitrary bending of the structure, and the magnetic field intensity distribution of the eigenmodes only changes with the direction of the air waveguide. Finally, the 3D simulation of the comb-shaped space-filling structure is carried out, from the *X*-*Z* section electric field diagram, it can be observed that the spoof localized surface plasmons generated by the structure can bind the energy on the surface of the structure and generate localized field enhancement. The space-filling design in this paper makes full use of the structure space. This highly localized structure can generate a higher Q-factor under the deep subwavelength structure, and the electromagnetic properties are not affected by the arbitrary bending of the metal structure, and have better stability. It provides a new idea for the preparation of nanometer-sized high-efficiency electromagnetic resonators.

Qiao X C, Shi T, Song S C, et al. Highly confined localized spoof plasmon resonance characteristics on space-filling curvilinear meta-structures[J]. *Opto-Electron Eng*, 2022, **49**(9): 220037; DOI: 10.12086/oee.2022.220037

Foundation item: National Natural Science Foundation of China (62075084), the Natural Science Foundation of Guangdong Province, China (2020A1515010615), the Fundamental Research Funds for the Central Universities of Ministry of Education of China (21620415), and Guangzhou Basic and Applied Basic Research Project (202102020566).

[1]Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Institute of Photonic Technology, Jinan University, Guangzhou, Guangdong 510632, China; [2]Guangxi Key Laboratory of Precision Navigation Technology and Application, Institute of Information and Communication, Guilin University of Electronic Technology, Guilin, Guangxi 541004, China

* E-mail: zilandeng@jnu.edu.cn