

太赫兹平行平板波导中等离子诱导透明效应的调控

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摘要 电磁波传播过程中的等离子诱导透明效应以其强烈的色散特性在慢光器件、光动态存储器件、高灵敏度传感器等方面有着广泛的应用前景,而亚波长周期超表面成为了实现此效应常用的手段之一。如何有效调控由亚波长周期超表面与外场相互作用而产生的等离子诱导透明效应则成为了研究的热点。采用太赫兹时域光谱技术对放置在平行平板波导中的等离子诱导透明超表面进行了系统研究。在外部横电模式的激励下,通过改变超表面的结构参数,在理论和实验上实现了基于平行平板波导-超表面系统的等离子诱导透明效应的有效调控。另外,还通过表面电流和电场绝对值分布的模拟对等离子诱导透明效应调控背后的机制进行了探究。所得结果可以为基于等离子诱导透明效应的可调控电磁器件的设计提供一种新的思路。

关键词 光谱学; 太赫兹技术; 平行平板波导; 亚波长周期超表面; 等离子诱导透明效应

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1 引言

电磁诱导透明效应是一种发生于三能级系统中的量子干涉效应,在外部激光的泵浦下会使得原本不透明的物质在一个特定频段内变得透明,在透射频谱上则表现为一个较宽且连续的谐振谷被一个尖锐的透明窗口所替代^[1-2]。尽管电磁诱导透明效应以其独特的强烈色散特性在诸如慢光器件^[3]、光动态存储器件^[4]、高灵敏度传感器^[5]等方面有着很广泛的实际应用,但其严苛的低温实验环境和稳定的气体激光源使其受到了许多限制。因此,由外部电磁场的诱导而能够呈现出类电磁诱导透明效应的亚波长周期超表面就成为实现此效应常用的手段之一^[6-9]。已有的报道基本是使用外场的电场分量作为激励源,磁场分量作为外场的另一个重要组成部分却很少被利用到。

在实际的应用中,控制电磁波的群速度已经成为了一种迫切的需要。在传统的量子等离子诱导透明效应实验的低温环境、稳定激光源的严苛背景下,研究者们或通过改变亚波长结构本身的结构参数^[7-8],或在亚波长结构中添加相变材料^[10-12],实现了寻常条件下被动或主动的等离子诱导透明效应的

有效调控。但直至目前,应用这些手段对等离子诱导透明效应进行调控还仅限于自由空间中,基于局域空间中的亚波长超表面结构的等离子诱导透明效应的调控研究还几乎没有被报道。

本课题组前期的工作^[13]将亚波长周期超表面中最基本的开口环结构与平行平板波导结合起来,在局域空间中实现了等离子诱导透明效应的有效调控。值得注意的是,与自由空间外部场正入射情况主要利用电场分量不同,“平行平板波导-超表面”系统中磁场分量起着重要的作用。虽然此工作已经通过在平行平板波导中放置不同布局的开口环阵列,初步实现了“平行平板波导-超表面”系统中的等离子诱导透明效应的调控,但还需进一步探索更加有效且有规律的调控手段。本文精心设计并制备了一系列基于开口环对的超表面样品,并且把这些样品放置于平行平板波导中,然后将此“平行平板波导-超表面”系统放置于太赫兹时域光谱仪中进行测试。相比于前期的工作,本文通过改变平行平板波导中开口环对元胞中的一个开口环的开口位置,在实验上实现了对等离子诱导透明效应“从有到无”的有效且有规律的调控,并且通过电磁仿真与耦合模理论对其进行了验证,最后对此调控现象背后的机

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制进行了探究。

2 实验装置、数值模拟与理论

2.1 实验装置

实验所使用的系统为 Advanced Photonics 公司生产的 T-Ray^R 5000 型太赫兹时域光谱仪。激励光电导天线的激光由光纤飞秒激光器产生,其波长为 1064 nm,重复频率和平均功率分别为 100 MHz 和 100 mW,脉冲宽度为 100 fs。由光电导天线受激发产生的太赫兹波经过半球硅透镜后形成平行光束,再通过一个半球聚乙烯透镜形成高斯光束,最后再通过另一个半球聚乙烯透镜和半球硅透镜被接收端的光电导天线所接收。光谱仪的窗口时间和采样频率分别为 320 ps 和 100 Hz,测试光谱的频率范围最高达 4 THz,信噪比为 80 dB。在实验中,为了能与太赫兹波有很强的相互作用,将“平行平板波导-超表面”系统放置于两个聚乙烯透镜之间的太赫兹波焦点处。当太赫兹波处于自由空间中时,光斑形状为圆斑;当太赫兹波被耦合进波导后,光斑的圆斑形状被“挤压”成线斑形状^[14]。

如图 1(a)所示,所使用的平行平板波导是对纯铜材质进行机械加工而得到的,其表面被精心抛光以减小波导表面对太赫兹波的散射^[14-15]。制作完成后的波导总长度为 $l_a = 120$ mm,宽度为 $l_b = 20$ mm。为了提高太赫兹波在自由空间与平行平板波导之间的耦合效率,波导的输入端与输出端均采用了微波波段常用的渐变喇叭结构^[16-18],其半径 $R = 203$ mm。渐变形状的喇叭结构能够有效减小波导对太赫兹波的反射,使得自由空间与平行平板波

导之间实现更好的阻抗匹配^[19]。另外从图 1(a)中还可以看出,平行平板波导的有效区域为一个位于波导中间位置的长方体空间,底面为 $l_b \times l_c = 20$ mm \times 20 mm 的正方形。为了使太赫兹波与超表面结构产生有效的电磁作用,采用 TE 模式(横电模)来激励超表面,即入射的太赫兹波的电场偏振方向平行于波导片,而磁场偏振方向垂直于波导片^[20]。

实验中所使用的超表面样品通过传统的光刻工艺制备,具体流程为:首先在石英基底上旋涂一层光刻胶,随后通过“光刻-显影”过程在光刻胶上制作出花纹,最后通过“蒸镀-剥离”过程得到铝材质的亚波长尺寸结构。图 1(b)为制作好的一个由两个开口环组成的典型开口环对样品的显微照片,可以看到沿着太赫兹波的传播方向排列着 8 个周期的开口环对元胞。超表面单个元胞尺寸为 $P_x \times P_y = 250$ μ m \times 95 μ m,石英基底的厚度为 400 μ m。图 1(c)为开口环对的具体尺寸,实际制作好的单个开口环为 $l_x \times l_z = 65$ μ m \times 65 μ m 的方形结构,线宽 $w = 4$ μ m,开口宽度 $g = 5$ μ m,两个开口环间的空隙宽度 $d = 5$ μ m,形成超表面结构的铝薄膜厚度 $h = 200$ nm。在 20 mm \times 20 mm \times 0.4 mm(长 \times 宽 \times 高)大小的石英基底上制作好亚波长结构阵列后,用另一块同样大小的石英基底覆盖于超表面样品上以形成“三明治”结构的待测试样品。随后通过精细的装配过程把待测试的“三明治”结构放入平行平板波导的有效区域内,最后把装配好的“平行平板波导-超表面”系统放置于太赫兹时域光谱仪的焦点处进行测试。另外,两块同样大小的石英基片被当作参考样品,也放入了平行平板波导中进行测试。

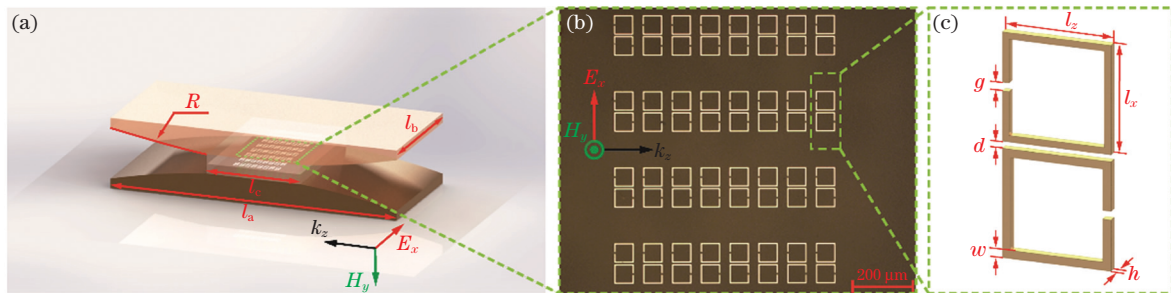


图 1 “平行平板波导-超表面”系统实验布局图。(a)“平行平板波导-超表面”系统图;(b)实验中用到的典型超表面的显微照片(标尺:200 μ m);(c)图 1(b)中开口环对的结构示意图

Fig. 1 Experimental setup of “parallel-plate waveguide-metasurface” system. (a) Diagram of “parallel-plate waveguide-metasurface” system; (b) microscopy image of typical metasurface used in this study (scale bar: 200 μ m); (c) structural diagram of split ring pair corresponding to Fig. 1(b)

在前期的工作中^[13],本课题组发现了外部入射的 TE 模式能够诱导平行平板波导中开口环对超表面结构中的等离子诱导透明效应,并对其潜在的电

磁响应机制进行了探讨。基于此前的工作,为了能对等离子诱导透明效应进行更有效的调控,制作了如图 2 所示的一系列超表面样品。这里将两个开口

环分别定义为环 1 和环 2,其中环 1 的结构参数固定不变,环 2 的开口分别沿着图 2 中的 x 轴与 z 轴移动,移动步长均为 $12.5 \mu\text{m}$ 。将环 2 的中间位置定为 0 点,图 2(a)~(e)分别为环 2 的开口沿着 x 轴从 $\delta x = -25 \mu\text{m}$ 的位置移动到 $\delta x = 25 \mu\text{m}$ 的开口环对超表面的显微照片;图 2(f)~(j)为环 2 的开口

沿着 z 轴移动的情况, δz 的范围也为 $-25 \sim 25 \mu\text{m}$ 。注意到,图 2(h)的结构类型和布局与已发表的文献[21]中的类似,其在砷化镓材料中可实现对光致类电磁诱导透明现象的动态调控,且工作在自由空间体系下,而本文研究的是波导体系下结构开口位置逐渐改变时的调控情况。

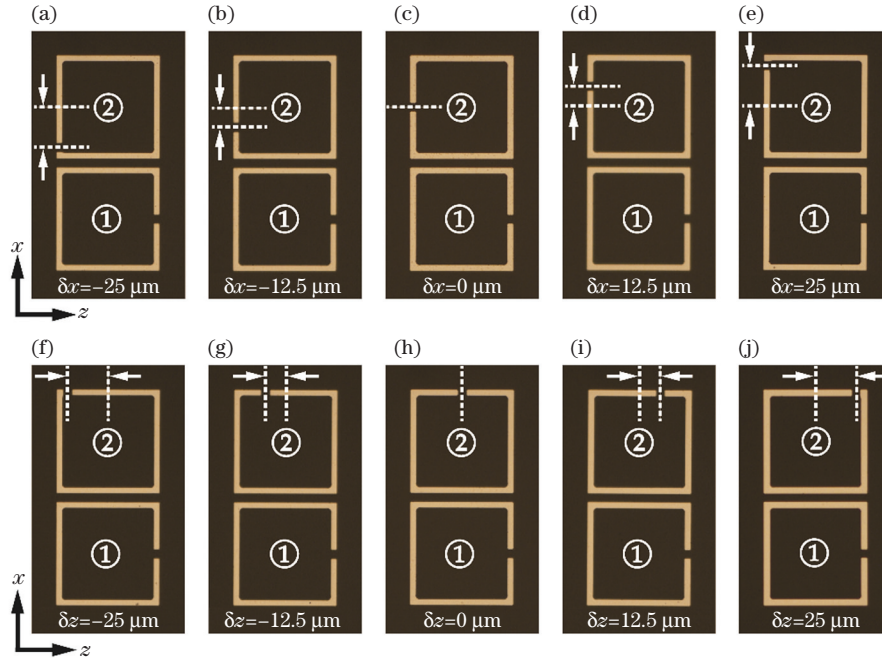


图 2 实验所制作的一系列超表面结构的显微照片。(a)~(e)环 2 的开口沿着 x 轴移动的情况;
(f)~(j)环 2 的开口沿着 z 轴移动的情况

Fig. 2 Microscopy images of a series of metasurfaces fabricated in experiment. (a)–(e) Movement of gap in split ring 2 along x axis; (f)–(j) movement of gap in split ring 2 along z axis

2.2 数值模拟

为了探索外部太赫兹波与平行平板波导中的超表面样品相互作用后所呈现出的电磁响应现象背后的机制,使用商用软件 Computer Simulation Technology 对特定频率处的表面电流与电场绝对值分布分别进行了模拟。其中,平行平板波导的模拟方法来源于微波频段的金属波导:采用时域求解器进行模拟,背景材料设置为 PEC,波导的入射边界与出射边界都被设置为电边界条件,波导的其他边界也都被设置为电边界条件。在模拟中不考虑实际平行平板波导的渐变喇叭端口,并且只在沿着太赫兹波传播方向建模一行有着 8 个周期的开口环对元胞。波导的馈源端口以及接收端口都设置为波端口,端口的尺寸都为 $680.2 \mu\text{m} \times 95 \mu\text{m}$ 的矩形。基底采用软件材料库中自带的无损耗石英 ($\epsilon = 3.75$),铝材质使用德鲁德模型^[22]来表示,其等离子频率 $\omega_p = 2.24 \times 10^{16} \text{ rad} \cdot \text{s}^{-1}$,碰撞频率 $\omega_c = 1.24 \times 10^{14} \text{ rad} \cdot \text{s}^{-1}$ 。

2.3 理论

基于耦合模理论^[23-26],对“平行平板波导-超表面”系统中的单个元胞内两个开口环间的相互耦合所产生的等离子诱导透明效应进行了分析。考虑一个有端口 1 和端口 2、模式 1 和模式 2 的双端口、双模式系统,则有

$$\frac{\partial}{\partial t} \psi_1 = (i\omega_1 - \gamma_{1i} - \gamma_{1e})\psi_1 + \Omega\psi_2 + d_{11}S_1^+, \quad (1)$$

$$\frac{\partial}{\partial t} \psi_2 = (i\omega_2 - \gamma_{2i} - \gamma_{2e})\psi_2 + \Omega\psi_1 + d_{21}S_1^+, \quad (2)$$

$$S_1^- = -ir_0S_1^+ + d_{11}\psi_1 + d_{12}\psi_2, \quad (3)$$

$$S_2^- = t_0S_1^+ + d_{21}\psi_1 + d_{22}\psi_2, \quad (4)$$

式中: ψ_m 、 ω_m 、 γ_{mi} 和 γ_{me} 分别表示模式 m ($m=1,2$) 的复振幅、谐振频率、固有损耗以及辐射损耗; Ω 、 d_{1m} (d_{2m}) 分别表示两个模式间、模式 1 (模式 2) 与 m 端口间的耦合强度; S_m^+ 与 S_m^- 分别表示沿着端口 m 输入、输出波的复振幅; r_0 与 t_0 分别表示系统空载时的反射与透射参数。

联立以上公式,可以推导出双端口、双模式系统的透过率公式:

$$t = 1 + \frac{W_2 d_{11} d_{21} + W_1 d_{12} d_{22} + \Omega(d_{11} d_{22} + d_{21} d_{12})}{W_1 W_2 - \Omega^2}, \quad (5)$$

式中: $W_m = i(\omega - \omega_m) + \gamma_{mi} + \gamma_{me}$ 。需要注意的是,这里的两个端口上的场分布为对称的。

3 结果与分析

3.1 环 2 的开口沿着 x 轴移动

在自由空间中,外部场激励开口环阵列必须至少满足以下两个条件之一^[27]:1)电场需含有极化方向平行于开口环开口的分量;2)磁场需含有极化方向垂直于开口环平面的分量。平行平板波导中存在两种模式^[28]:1)电场极化方向平行于波导、磁场极化方向垂直于波导的 TE 模式;2)电磁场极化方向

与 TE 模式相反的 TM 模式。前期工作^[13]已经对平行平板波导中的开口环(对)阵列在外部太赫兹波的作用下所呈现出的电磁响应机制进行了很详细的研究,研究发现:1)当开口环的开口平行于外部电场分量的偏振方向时,开口环受到外部电场分量和磁场分量的联合激励;2)当开口环的开口垂直于外部电场分量的偏振方向时,开口环只受到外部电场分量的激励。此外,研究还发现平行平板波导中同时受到电场分量与磁场分量激励的单环阵列的谐振强度要强于只受到磁场分量激励的单环阵列,另外单环开口处积聚的电场也比后者强,这说明前者在二维材料传感方面有着更大的优势^[29]。图 3(a)~(c)分别表示在外部 TE 模式的激励下,平行平板波导中对应于图 2(a)~(e)的开口环对的实验、电磁模拟与理论拟合的透射频谱结果。从图中可以看出三者吻合得很好,产生微小差别的原因可能是:1)制备

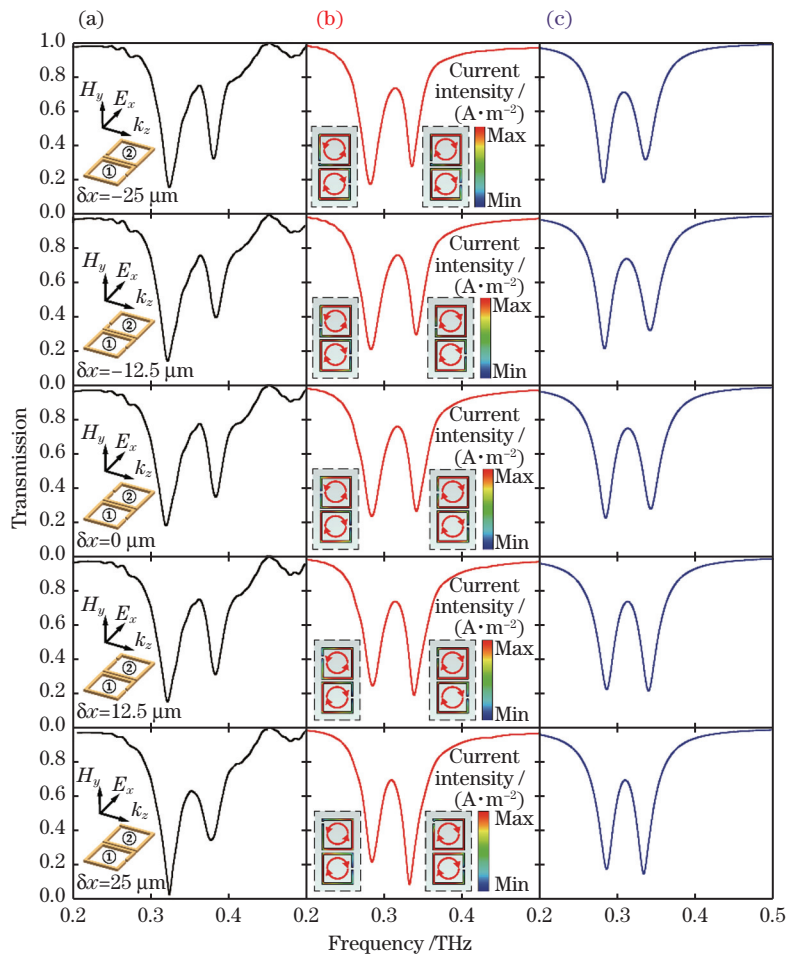


图 3 环 2 的开口沿着 x 轴移动时的透射频谱。(a)实验结果,插图为谐振频率处的表面电流分布;(b)仿真结果,插图为谐振频率处的表面电流分布;(c)理论拟合结果

Fig. 3 Transmission spectra when the gap in split ring 2 is moved along the x axis. (a) Experimental results (the inset in each subfigure is the corresponding metasurface arrangement); (b) simulated results (the insets display the surface current distributions at the resonance frequencies); (c) theoretically fitted results

超表面结构过程中的工艺误差;2)实验中所使用的石英基底介电常数与电磁模拟中的有所不同;3)平行平板波导的装配误差^[30]。从图 3 中可以看出,当将图 2(a)~(e)中的开口环阵列放置于平行平板波导中时,在外部 TE 模式的诱导下,在一个较宽且连续的谐振频谱中出现一个透明窗口,呈现出典型的等离子诱导透明效应。环 2 的开口位置从 $\delta x = -25 \mu\text{m}$ 变换到 $\delta x = 25 \mu\text{m}$ 的过程中,透射频谱的曲线形状没有明显的改变;当 δx 的值为 $25 \mu\text{m}$ 时,虽然透射频谱的曲线形状有了微小的改变,但总体上并不能对“平行平板波导-超表面”系统的等离子诱导透明效应进行有效的调控。

如前期工作^[13]所述,将对称的单开口环阵列放入平行平板波导中时,在外部 TE 模式的激励下开口环上出现诱导的环形电流,进而呈现出 LC 谐振响应^[27,31]。但如果将对称的单个开口环替换为图 2(c)中的对称开口环对时,透射频谱曲线上所表示的模式会从一个劈裂成两个。有趣的是,类似的对称开口环对布局在自由空间中只会表现出单谐振谷现象^[32]。在这里,分析两个开口环间的耦合时只考虑环间的电感耦合,这是由于两个开口环的开口或者距离很远或者互相垂直,使得两个开口环间的电容耦合很弱。当环 2 的开口沿着 x 轴移动时,由外部场激励的开口环上的磁场并没有大的变化,再加上开口环间的耦合方式主要为磁性的电感耦合,这就导致了图 3 中不同开口环对布局的透射频谱曲线形状没有发生明显的改变。图 3(b)中的插图给出了透射频谱中两个谐振频率处的表面电流分布,可以看出不管环 2 的开口沿着 x 轴如何移动,两个谐振频率处的表面电流分布特性都非常类似,开口环对在较低谐振频率处的表面电流为反相位,较高谐振频率处则为

同相位。这里可以从等离子杂化理论角度来解释开口环对的表面电流分布特性^[32],需要注意的是这里只考虑两个开口环间的磁偶极矩耦合。无论 δx 为何值,所有谐振频率处的两个磁偶极矩都呈现出了横向耦合特性,且较低谐振频率处都呈现出反对称谐振模式特性,较高谐振频率处则表现出对称谐振模式特性。反对称模式会使得两个开口环上的能量减小,导致此谐振点位于较低的频率,而对称模式则相反。

为了进一步解释平行平板波导中的开口环对在外部 TE 模式激励下所呈现出的等离子诱导透明效应,对透明窗口处的电场绝对值分布进行了模拟,如图 4 所示。从图中可以发现,在外部太赫兹兹波的电场分量和磁场分量几乎同等的激励下,只有环 2 的开口区域处有着强烈的电场局域现象。这种反常的现象要归咎于两个开口环间的亚波长近场耦合。这可以从自由空间中经典的明、暗模式耦合的角度进行理解^[6-8,10,21,33],当受外部场激励的明模式与被外部场激励的暗模式间的距离不能很小时,明模式通过近场与暗模式相互耦合。在不同模式间的相消干涉作用下,原本受到外部场激励而激发的明模式会受到抑制,而暗模式则通过明模式的近场耦合被激发,两个模式的损耗被抑制,从而呈现出电磁诱导透明效应。在本文的情况中,即使两个开口环都能受到外场的激励,都能当作明模式;但在近场耦合作用下,环 1 明显作为明模式被抑制,而环 2 作为暗模式被激发。从以上分析可知,与以往的明、暗模式耦合不同,在本文所研究的情况下不能通过外部场激励来确认明模式与暗模式,而需要通过模拟手段来确认哪一个环为明模式,哪一个环为暗模式。

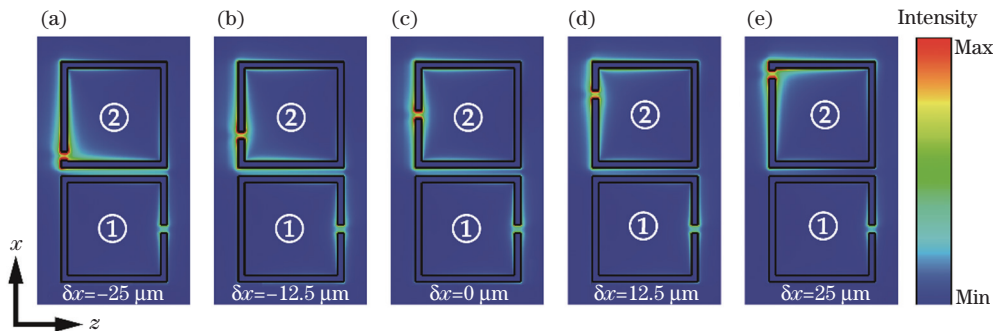


图 4 对应于图 3(b)中透明窗口频率处的电场绝对值分布。(a) $\delta x = -25 \mu\text{m}$; (b) $\delta x = -12.5 \mu\text{m}$; (c) $\delta x = 0 \mu\text{m}$; (d) $\delta x = 12.5 \mu\text{m}$; (e) $\delta x = 25 \mu\text{m}$

Fig. 4 Electric field absolute distributions at transmission window frequencies corresponding to Fig. 3(b).

(a) $\delta x = -25 \mu\text{m}$; (b) $\delta x = -12.5 \mu\text{m}$; (c) $\delta x = 0 \mu\text{m}$; (d) $\delta x = 12.5 \mu\text{m}$; (e) $\delta x = 25 \mu\text{m}$

3.2 环 2 的开口沿着 z 轴移动

当开口环的开口垂直于外部电场分量的偏振方向时,对称开口环阵列不会受到外部电场分量的激励^[27]。一旦开口环结构由于其开口的移动而变得不对称时,无论此非对称开口环结构位于自由空间中还是平行平板波导中,偏振方向垂直于环开口的外部电场分量都会在非对称开口环上诱导补偿电流,进而在环上产生环形电流,使得此非对称开口环也能呈现出 LC 谐振响应。已有的报道中^[34-35]已经详细地阐述了此种现象背后的电磁响应机制。

在这里,为了对“平行平板波导-超表面”系统在外外部 TE 模式激励下所呈现出的等离子诱导透明效应进行有效的调控,进一步对环 2 的开口沿着 z 轴移动的情况进行了探究,具体布局如图 2(f)~(j)所示。如前所述,在外外部 TE 模式的激励下,平行平板波导中的环 2 除了开口位于 $\delta z = 0 \mu\text{m}$ 情况外,都会受到

除了外部磁场分量外的电场分量的激励。图 5 为环 2 开口沿着 z 轴移动时的实验、电磁模拟与理论拟合的透射频谱结果,可以看出三者仍然吻合得很好。值得注意的是,随着环 2 开口的移动,由外部 TE 模式诱导的等离子诱导透明效应逐渐减弱,当 $\delta z = 25 \mu\text{m}$ 时透明窗口彻底消失。图 5 所呈现出的曲线特性说明沿着 z 轴移动环 2 开口的行为可以对“平行平板波导-超表面”系统与外场相互作用后的等离子诱导透明效应进行有效的调控。图 5(b)中的插图同样给出了透射频谱谐振频率处的表面电流分布,当 $\delta z = -25 \mu\text{m}$ 时,两个谐振频率处的表面电流分布遵从环 2 开口沿着 x 轴移动的特性;当 $\delta z = 25 \mu\text{m}$ 时,等离子诱导透明效应导致的双谐振谷会退化成单谐振谷,从谐振频率处的表面电流分布可以看出此模式为对称模式。当环 2 的开口位于 $-25 \mu\text{m}$ 和 $25 \mu\text{m}$ 之间时,开口环对上的表面电流分布特性为两种模式的“叠加”。

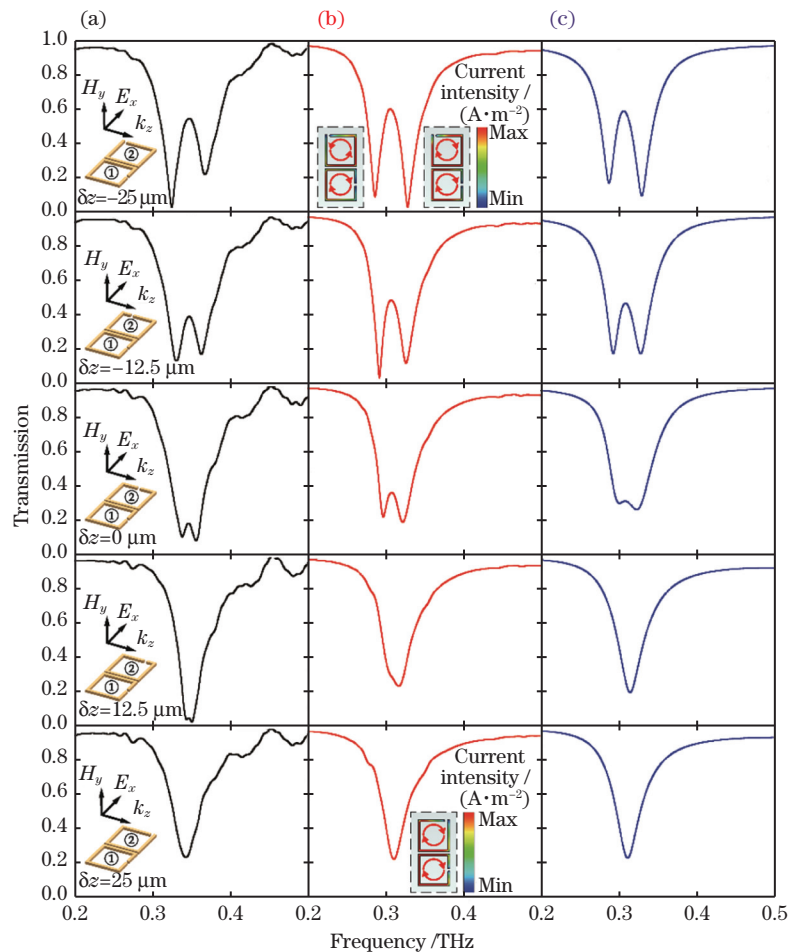


图 5 环 2 的开口沿着 z 轴移动时的透射频谱。(a) 实验结果,插图为相应的超表面布局;

(b) 仿真结果,插图为谐振频率处的表面电流分布;(c) 理论拟合结果

Fig. 5 Transmission spectra when the gap in split ring 2 is moved along the z axis. (a) Experimental results (the inset in each subfigure is the corresponding metasurface arrangement); (b) simulated results (the insets display the surface current distributions at the resonance frequencies); (c) theoretically fitted results

本文同样对图 5 中透明窗口处的电场绝对值分布进行了模拟,如图 6 所示。当环 2 的开口沿着 z 轴移动时,当作暗模式的环 2 开口区域处的电场强度基本没有发生变化,而作为明模式的环 1 开口区域处的电场的变化却非常明显,从几乎没有电场分布到电场强度比环 2 还强。这样的电场分布特性说明随着环 2 开口的移动,环 2 模式抑制环 1 模式的能力越来越弱。当开口移动到 $\delta z = 25 \mu\text{m}$ 的位置时,环 1 开口区域处的电场强度达到最大,环 2 模式抑制环 1 模式的能力彻底消失。另外与平行平板波导中只存在环 1 或环 2 的情况^[13]相比,此时的透射频谱中的谐振频率的移动量很小,几乎可以忽略。谐振频率没有移动的现象可以用两个环间的耦合方

式来解释。电容耦合的静电特性使得其耦合强度要大于磁性的电感耦合,并且电容耦合与电感耦合带来的频率移动效果能够互相抵消^[36]。当环 2 的开口沿着 z 轴移动时,两个开口环的开口即使互相垂直,但由于空间距离的变小,开口环间的电容耦合逐渐变强,使得两个开口环间电容耦合与电感耦合在 $\delta z = 25 \mu\text{m}$ 时达成了某种平衡,谐振频率既不红移也不蓝移。 $\delta z = 25 \mu\text{m}$ 的开口环对布局与单个开口环在透射频谱曲线上的最大区别为两者的谐振线宽,开口环对的谐振线宽要宽一些。这是由于两个开口环上的表面电流分布是同相的,辐射场的相长干涉产生了强烈的散射现象,最后形成了高辐射损耗的谐振模式^[37]。

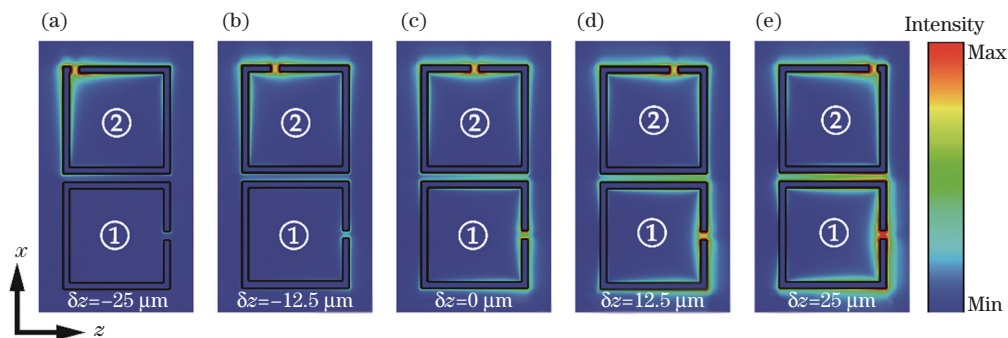


图 6 对应于图 5(b)的透明窗口频率处的电场绝对值分布。

(a) $\delta z = -25 \mu\text{m}$; (b) $\delta z = -12.5 \mu\text{m}$; (c) $\delta z = 0 \mu\text{m}$; (d) $\delta z = 12.5 \mu\text{m}$; (e) $\delta z = 25 \mu\text{m}$

Fig. 6 Electric field absolute distributions at transmission window frequencies corresponding to Fig. 5(b).

(a) $\delta z = -25 \mu\text{m}$; (b) $\delta z = -12.5 \mu\text{m}$; (c) $\delta z = 0 \mu\text{m}$; (d) $\delta z = 12.5 \mu\text{m}$; (e) $\delta z = 25 \mu\text{m}$

4 结 论

在外部 TE 模式的激励下,通过改变平行平板波导中超表面元胞内的开口环对的结构参数,从实验上实现了对“平行平板波导-超表面”系统中的等离子诱导透明效应的有效调控。对透射频谱中特定频率处的表面电流分布、电场绝对值分布进行了模拟,分析了“平行平板波导-超表面”系统在外外部 TE 模式激励下所呈现的电磁响应现象背后的机制。结果表明:在等离子诱导透明的窗口频率处,受到外部几乎同等激励条件下的两个开口环中的一个开口环的开口区域处的电场会被抑制。通过改变此开口环的开口位置,环上的抑制效果逐渐减弱直至消失,说明这个开口环为明模式。本文研究成果可以为慢光器件、光动态存储器、高灵敏度传感器的设计提供一种新的思路。

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Modulation of Plasmon-Induced Transparency Effect in Terahertz Parallel-Plate Waveguide

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Abstract

Objective Plasmon-induced transparency (PIT) is a quantum interference effect occurring in three-energy-level systems. Under an external laser pump, a substance that is originally opaque becomes transparent within a specific frequency range, and a wide and continuous resonance dip is replaced by a sharp transparency window in the transmission spectrum. Due to its strong dispersion, the PIT effect occurring during electromagnetic wave transmission has great potential for applications such as slow-light devices, optical dynamic storage devices, and high-sensitivity sensors. Subwavelength periodic metasurfaces are one of the most widely used methods to achieve the PIT effect for electromagnetic waves. In previous reports, the external electric field component was usually used as the excitation source, and the magnetic field component, which is an important component of the external field, was rarely used. The aim of current research is to effectively manipulate the PIT effect arising from the interaction between a subwavelength periodic metasurface and the external field. In this study, terahertz (THz) time-domain spectroscopy is adopted to perform a systematic study of PIT metasurfaces placed in a parallel-plate waveguide (PPWG). Under external TE mode excitation, effective modulation of the PIT effect based on a PPWG metasurface system is realized by varying the structural parameters of the metasurfaces both theoretically and experimentally. Our design may provide a new strategy for the design of tunable electromagnetic devices based on the PIT effect.

Methods Based on our previous work, we designed and fabricated a series of aluminum split-ring resonator pairs (SRRPs) with different gap locations on a quartz substrate. There were eight periods of SRRPs along the wave propagation direction, and the gap in split-ring 2 was moved along the x and y axes [Figs. 1(b) and 2]. Then, the sandwich structures (quartz substrate-aluminum structures-quartz substrates) were inserted into a copper PPWG for characterization. The input and output ends of the waveguide were tapered to increase the conversion efficiency from free-space THz radiation to waveguide modes.

To verify the experimental results, SRRPs with the same geometric parameters were simulated using CST Microwave Studio, and the coupled mode theory was used to fit the simulated results. The underlying mechanism of the modulation of the PIT effect was understood through simulations of the surface current and absolute electric field distributions at the frequencies of interest. In simulations, the TE mode of the PPWG was applied to excite the SRRPs; that is, the electric field was parallel to the waveguide plates, and the magnetic field was perpendicular to

the waveguide plates. The time-domain solver was adopted, and the background was set as a perfect electric conductor. The electric boundary condition was assigned to all directions, and waveguide ports were set to the input and output ends of the waveguide. In simulations, only one row with eight SRRPs was modeled along the direction of the guided wave, and the aluminum and the quartz substrate were treated as the Drude model and lossless dielectric, respectively. The tapered parts of the waveguide were not considered in the simulations.

Results and Discussions The transmission spectra for the gap in split-ring 2 moving along the x and y axes were measured, simulated, and fitted. The results (Figs. 3 and 5) indicate that the experimental, simulated, and fitted results agreed well. When the gap in split-ring 2 was moved along the x axis, the PIT effect occurred due to the interaction between the subwavelength periodic metasurface and the external field. However, the PIT effect could not be manipulated effectively by changing the gap position. When the gap in split-ring 2 was displaced along the z axis, the transmission spectra demonstrated that the PIT effect gradually disappeared.

To understand the underlying mechanism of the PIT effect, the surface currents in the SRRPs at the resonance dips were simulated. The insets of Figs. 3(b) and 5(b) demonstrate that an antisymmetric mode appeared at the lower resonance frequency, where as a symmetric mode appeared at the higher frequency. When $\delta z = 25 \mu\text{m}$, the PIT effect vanished, and the single resonance mode was a symmetric mode. The above simulated results are consistent with the plasmon hybridization picture.

The underlying mechanism of the PIT effect was also analyzed by simulating the absolute electric field distributions at the PIT window frequencies. As depicted in Fig. 4, the absolute electric field was mainly confined in the gap of split-ring 2, and there was a weak electric field distribution in the gap of split-ring 1 under the same excitation conditions. It is interesting that the intensity of the electric field in the gap of split-ring 1 became stronger when the gap in split-ring 2 was moved (Fig. 6). The absolute electric field distributions in the SRRPs can be explained by the bright-dark mode coupling theory, where split rings 1 and 2 can be treated as the bright and dark modes, respectively. Though the two rings can be excited by the external field, the bright mode can be suppressed by the dark mode through the deep-subwavelength distance between their adjacent arms.

Conclusions Under external TE mode excitation, effective modulation of the PIT effect based on a PPWG metasurface system is realized by varying the structural parameters of the metasurfaces experimentally. The underlying mechanism of the PIT effect is analyzed through simulations of the surface current and absolute electric field distributions at the frequencies of interest. The simulated results demonstrate that the electric field in one ring is suppressed by another ring under the same excitation source at the PIT window frequencies, and the suppression effect can be controlled by varying the structural parameters of the SRRPs. Our work may open new avenues for slow-light devices, optical dynamic storage devices, and high-sensitivity sensors.

Key words spectroscopy; terahertz technology; parallel-plate waveguide; subwavelength periodic metasurface; plasmon-induced transparency effect

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