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Deep-subwavelength magnetic-coupling-dominant interaction among magnetic localized surface plasmons

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Magnetic coupling is generally much weaker than electric Coulomb interaction. This also applies to the well-known magnetic “meta-atoms,” or split-ring resonators (SRRs) as originally proposed by Pendry *et al.* [IEEE Trans. Microwave Theory Tech. **47**, 2075 (1999)], in which the associated electric dipole moments usually dictate their interaction. As a result, stereometamaterials, a stack of identical SRRs, were found with electric coupling so strong that the dispersion from merely magnetic coupling was overturned. Recently, other workers have proposed a new concept of magnetic localized surface plasmons, supported on metallic spiral structures (MSSs) at a deep-subwavelength scale. Here, we experimentally demonstrate that a stack of these magnetic “meta-atoms” can have dominant magnetic coupling in both of its two configurations. This allows magnetic-coupling-dominant energy transport along a one-dimensional stack of MSSs, as demonstrated with near-field transmission measurement. Our work not only applies this type of magnetic “meta-atom” into metamaterial construction, but also provides possibilities of magnetic metamaterial design in which the electric interaction no longer takes precedence.

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I. INTRODUCTION

The field of metamaterials was greatly stimulated by the invention of split-ring resonators (SRRs) [1], as originally proposed by Pendry *et al.*, which can generate strong magnetic moments at a deep-subwavelength scale. However, it is well known that SRRs also carry substantial electric moments, which often dictate the interaction between adjacent SRRs. This in turn has complicated the design for magnetic metamaterials [2–4]. For example, a stack of SRRs, termed “stereometamaterials” [2] as analogous to stereoisomers in chemistry, has a crucial interplay between the magnetic coupling and electric coupling, the stronger strength of the latter leading to dispersion crossing when the spatial arrangement of SRRs is tuned. Furthermore, it has been shown that a chain of subwavelength plasmonic particles can transport electromagnetic (EM) energy based on electric coupling [5–11] or direct electric current exchange [12–14]. However, more work needs to be done on this energy transport phenomenon with dominant magnetic coupling.

Recently, the concept of localized surface plasmon is extended to lower frequency [15–17] and Garcia-Vidal, Cui, Pendry, and co-workers proposed a new concept of magnetic localized surface plasmons, magnetic dipole modes supported on metallic spiral structures (MSSs) at a deep-subwavelength scale [18]. Although these new magnetic “meta-atoms” have been studied individually [18,19], a stack of them, or MSS stereometamaterials, have not been studied yet. In this paper, we first theoretically and experimentally study a dimer of stacked MSSs. We demonstrate that its resonance properties can be modified by altering the stacking symmetry between two identical MSS resonators, similar to previous SRR stereometamaterials. Analysis based on Lagrangian formalism

[12] shows that the magnetic interaction, rather than the electric interaction, is the dominant coupling mechanism. Second, we also demonstrate that a one-dimensional vertical chain of MSSs can efficiently transport EM energy in a deep-subwavelength scale with preserved magnetic mode profile.

II. NUMERICAL SIMULATIONS

We first illustrate the two configurations of a MSS dimer in Fig. 1. Each MSS in the dimer consists of four spiral arms with width $w = 0.5$ mm, which are axially wrapped by 1.5 turns with outer radius $R = 12.5$ mm. The spacing of neighboring arms at the outer radius is $d = 1.5$ mm. Although the two MSSs in the dimer are identical, configurations of symmetric [Fig. 1(a)] and antisymmetric [Fig. 1(b)] stacking can be arranged. The inter-MSS distance is set as $h = 6$ mm.

To study the EM response of these MSS dimers, numerical simulations are performed based on a commercial finite-integration time domain software, CST MICROWAVE STUDIO. In the numerical calculations, metal is modeled as a perfect electric conductor (PEC). As indicated in Fig. 1(a), a discrete port (dipole current) excites the resonance in the dimer, and a probe is employed to detect the local E_z field at the position 1 mm above the center of the upper MSS. Simulated near-field response spectra of the two different stacking configurations compared with the case of only one MSS are shown in Fig. 2. Each stacking configuration has two observable resonances, ω_s^- and ω_s^+ , for symmetric stacking ($\omega_s^- = 1.88$ GHz and $\omega_s^+ = 2.18$ GHz in Fig. 2) and ω_a^- and ω_a^+ for antisymmetric stacking ($\omega_a^- = 1.67$ GHz and $\omega_a^+ = 2.46$ GHz in Fig. 2), which are split from the resonance ω_0 of the single MSS ($\omega_0 = 1.99$ GHz in Fig. 2). As studied previously, this resonance ω_0 of a single MSS corresponds to a magnetic dipole mode of localized surface plasmons [18,19], but how adjacent magnetic MSSs interact through magnetic coupling is still unknown.

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FIG. 1. Schematic of symmetric (a) and antisymmetric (b) stacking configurations of two vertically coupled metallic spiral structures. Two monopole antennas indicated by two black arrows are used to excite and probe the resonances. The ultrathin metallic spiral structure (thickness 0.018 mm) has outer radius $R = 12.5$ mm. The width of spiral strips is $w = 0.5$ mm. The spacing between neighboring stripes is $d = 1.5$ mm at the outer radius.

To understand these resonance properties, we further simulate in Fig. 3 the corresponding distributions of currents, magnetic fields, and electric fields for the resonances revealed above. It can be seen that on each MSS, electric currents form a major current loop, generating a strong magnetic dipole moment [18]. For the symmetrically stacked MSS dimer, the magnetic dipole moments (μ) of the two MSSs are aligned parallel at the lower resonance frequency ω_s^- [Fig. 3(a)], and antiparallel at the higher resonance frequency ω_s^+ [Fig. 3(b)]. This is consistent with the magnetic field distributions in Figs. 3(a) and 3(b). In Fig. 3(a), the magnetic fields go through these two MSSs continuously, which means the north pole of the upper MSS and the south pole of the lower MSS face each other, causing an attractive force between them. This attractive force lowers the resonance frequency from ω_0 of a single MSS to ω_s^- when two MSSs are combined. On the contrary, at the higher resonance frequency ω_s^+ , as shown in Fig. 3(b), the magnetic fields from these two MSSs repel in the middle region, because two like magnetic poles of MSSs face each other. This repulsive force

FIG. 2. Simulated near-field response spectra of two vertically coupled metallic spiral structures with symmetric stacking configuration (blue line) and antisymmetric stacking configuration (red line), compared with the near-field response spectrum of a single metallic spiral structure (black line).

raises the resonance frequency from ω_0 of a single MSS to ω_s^+ when two MSSs are combined. Note that these quasistatic “attractive”/“repulsive” forces analyses are valid only when the dimensions of MSS (~ 2.5 cm) are much smaller than the operating wavelength (~ 15 cm).

This resonance frequency splitting mechanism based on magnetic coupling also applies to the antisymmetrically stacked MSS dimer. As shown in Figs. 3(c) and 3(d), each MSS in this antisymmetric stacking configuration still carries a major current loop with a strong magnetic dipole moment. At the lower resonance frequency ω_a^- , the magnetic dipole moments of the upper and lower MSSs are aligned parallel [Fig. 3(c)]. At the higher resonance frequency ω_a^+ , they are aligned antiparallel [Fig. 3(d)]. After comparing their magnetic field distributions in Fig. 3(c) and Fig. 3(d), we can deduce, from the same reason analyzed in the symmetric stacking configuration, that the resonance frequency splitting, from ω_0 of a single MSS to ω_a^- and ω_a^+ when two MSSs are combined in the antisymmetric stacking configuration, is also because of the magnetic coupling between these two MSSs.

Despite similar magnetic coupling, the frequency differences of lower and higher resonance frequencies in the two stacking configurations are different. We need to consider the electric coupling to account for this difference. Because of the spiral geometry of MSS, the current loop [e.g., the upper MSS in Fig. 3(a)] with a downward magnetic moment must be associated with radial currents flowing inwards, generating radially oriented electric dipoles (p) and accumulating positive charges at the center. Therefore, for the symmetrically stacked MSS dimer, when the magnetic dipoles of upper and lower MSSs are aligned parallel at the lower resonance frequency ω_s^- [Fig. 3(a)] with an attractive magnetic force, the accumulated like charges on the upper and lower MSSs repel each other and generate a repulsive force, which can be inferred from the electric field distribution in Fig. 3(a). This repulsive force partially offsets the magnetic attractive force. On the other hand, at the higher resonance frequency ω_s^+ , as shown in Fig. 3(b), when the magnetic dipoles of upper and lower MSSs are aligned antiparallel, the associated radial currents for the upper and lower MSSs are antiparallel. The accumulated opposite charges on the upper and lower MSSs generate an attractive magnetic force, which partially offsets the repulsive magnetic force.

However, in the antisymmetrically stacked MSS dimer, the weak electric force no longer offsets the strong magnetic force. As shown in Fig. 3(c), because of the antisymmetric stacking, the parallelly aligned magnetic moments at the lower resonance frequency ω_a^- are associated with antiparallel radial currents at the upper and lower MSSs. These antiparallel radial currents will accumulate opposite charges at the center of MSSs, and generate an attractive electric force, as can be inferred from the electric field distribution in Fig. 3(c). Similarly, at the higher resonance frequency ω_a^+ , the antiparallel magnetic moments are associated with parallel radial currents on the upper and lower MSSs [Fig. 3(d)], which accumulate like charges at the center of MSSs and generate a repulsive electric force, as can be inferred from the electric field distribution in Fig. 3(d). Therefore, in the antisymmetric stacking, the weak electric force always enhances the strong magnetic force,

FIG. 3. Resonance modes analysis on the two vertically coupled metallic spiral structures. The current distribution, the alignment of the magnetic and electric dipoles, the magnetic field distribution, and the electric field distribution at the (a) lower resonance frequency (ω_s^-) and the (b) higher resonance frequency (ω_s^+) of symmetric stacked dimer, and at the (c) lower resonance frequency (ω_a^-) and the (d) higher resonance frequency (ω_a^+) of antisymmetric stacked dimer.

leading to a wider frequency splitting for the MSS dimer, i.e., $\omega_a^- < \omega_s^- < \omega_s^+ < \omega_a^+$.

We then quantitatively compare the magnetic-coupling strength and electric-coupling strength. A single MSS can be modeled as an equivalent LC circuit with resonance frequency $\omega_0 = 1/(LC)^{1/2}$, where the four spiral arms carry inductance L and gaps between neighboring spiral arms carry capacitance C . Similar to previous Lagrangian formalism for a SRR dimer [2], we can write down the Lagrangian for this MSS dimer system as follows:

$$\Gamma = \frac{L}{2}(\dot{q}_1^2 - \omega_0^2 q_1^2) + \frac{L}{2}(\dot{q}_2^2 - \omega_0^2 q_2^2) + M_H \dot{q}_1 \dot{q}_2 \pm M_E \omega_0^2 q_1 q_2, \quad (1)$$

where q_m ($\dot{q}_m$) represents the charge (current) accumulated on the m th MSS, and M_H and M_E quantify the magnetic and electric couplings, respectively. The sign of “ $\pm$ ” before the last item takes “ $-$ ” for the symmetric stacking and “ $+$ ” for the antisymmetric stacking. Substituting Eq. (1) into the Euler-Lagrange equations:

$$\frac{d}{dt} \left(\frac{\partial \Gamma}{\partial \dot{q}_m} \right) - \frac{\partial \Gamma}{\partial q_m} = 0, \quad (m = 1, 2). \quad (2)$$

We can obtain the eigenfrequencies of the MSS dimer system as

$$\begin{aligned} \omega_s^- &= \omega_0 \sqrt{\frac{1 + \kappa_{Es}}{1 + \kappa_{Hs}}} \\ \omega_s^+ &= \omega_0 \sqrt{\frac{1 - \kappa_{Es}}{1 - \kappa_{Hs}}}, \end{aligned} \quad (3)$$

for the symmetric stacking configuration and

$$\begin{aligned} \omega_a^- &= \omega_0 \sqrt{\frac{1 - \kappa_{Ea}}{1 + \kappa_{Ha}}} \\ \omega_a^+ &= \omega_0 \sqrt{\frac{1 + \kappa_{Ea}}{1 - \kappa_{Ha}}}, \end{aligned} \quad (4)$$

for the antisymmetric stacking configuration, where $\kappa_{Es}(\kappa_{Ea}) = M_{Es}(M_{Ea})/L$, $\kappa_{Hs}(\kappa_{Ha}) = M_{Hs}(M_{Ha})/L$ are the electric and magnetic-coupling strengths for the symmetric (antisymmetric) stacking configuration, respectively. Fitting the simulated resonance frequencies with the above expressions yields the corresponding coupling coefficients as $\kappa_{Hs} = 0.284$, $\kappa_{Es} = 0.134$, $\kappa_{Ha} = 0.279$, and $\kappa_{Ea} = 0.105$. Notably, for both stacking configurations, the magnetic-coupling

FIG. 4. (a) The measured near-field response spectra of a single metallic spiral structure (black triangles), two vertically coupled metallic spiral structures with symmetric (blue squares) and antisymmetric (red circles) stacking configurations. (b1,b2) The measured E_z field patterns on two transverse planes 1 mm above and below the stacked dimer with symmetric stacking configuration at lower resonance frequency ω_s^0 [1.71 GHz (b1)] and higher frequency ω_s^π [1.95 GHz (b2)]. (c1,c2) The measured E_z field patterns on two transverse planes 1 mm above and below the stacked dimer with antisymmetric stacking configuration at lower resonance frequency ω_a^π [1.51 GHz (c1)] and higher frequency ω_a^0 [2.18 GHz (c2)].

strength is always much larger than the electric-coupling strength. Note that although we only used four resonances' frequencies for Lagrangian fitting, they are representative for different stacking angles. Measured results in Fig. S2 of the Supplemental Material [20] show that these split resonance frequencies of vertically coupled MSSs are very stable with varying stacking angles, meaning that the retrieved coupling factors will not change even more measurements with different stacking angles considered.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

We then proceed to experimentally demonstrate the mode splitting of the MSS dimers. By using standard printed circuit-board fabrication, we printed 18- μm -thick MSSs on 200- μm -thick FR4 dielectric substrate. A foam plate (ROHACELL 71 HF, relative permittivity $\varepsilon = 1.075$, thickness $h = 6$ mm) was used as a spacer between two identical MSSs. The near-field response spectra were measured with a pair of monopole antennas as the source and the probe, as indicated in Fig. 1(a), connected to a vector network analyzer (R&S ZVL-13). The measured results are shown in Fig. 4(a). It can be seen that the resonance peak of a single MSS ($\Omega = 1.82$ GHz) is split into two distinct resonance peaks at frequencies $\omega_s^0 = 1.71$ GHz and $\omega_s^\pi = 1.95$ GHz for symmetric stacking, and $\omega_a^\pi = 1.51$ GHz and $\omega_a^0 = 2.18$ GHz for antisymmetric stacking, respectively, where the superscripts π and 0 denote the relative phase between the electric fields of two MSSs. Note that because of the 200- μm -thick FR4 substrate, all resonance peaks are redshifted slightly compared to the simulation results in Fig. 2. It is worth mentioning that, besides the fundamental magnetic localized surface plasmon mode (magnetic dipole mode M_1), the metallic spiral structure also supports the fundamental electric localized surface plasmon mode (electric dipole mode E_1) and other high-order modes (e.g., high-order electric localized surface plasmon modes E_2 - E_3 , high-order magnetic localized surface plasmon modes M_2 - M_3) [19]. We present the mode splitting of other five

electric/magnetic localized surface plasmon modes in Fig. S1 in the Supplemental Material [20].

We further present the measured near-field distributions (E_z) on the top and bottom transverse planes of the MSS dimers for the symmetric stacking configuration [Figs. 4(b1) and 4(b2)] and the antisymmetric stacking configuration [Figs. 4(c1) and 4(c2)]. Clearly, the phase difference between top and bottom MSS in the symmetric stacking configuration is $\Delta\theta = 0$ at the lower resonance frequency (ω_s^0) [Fig. 4(b1)] and $\Delta\theta = \pi$ at the higher resonance frequency (ω_s^π) [Fig. 4(b2)]. Yet the phase difference between the top and bottom MSS in the antisymmetric stacking configuration is $\Delta\theta = \pi$ at the lower frequency (ω_a^π) [Fig. 4(c1)] and $\Delta\theta = 0$ at the higher frequency (ω_a^0) [Fig. 4(c2)]. Note that although the electric interaction enhances the magnetic interaction in the antisymmetric MSS dimer and offsets the magnetic interaction in the symmetric MSS dimer, the signs of the total coupling coefficients are still determined by the magnetic interaction. Thus the sign of the total coupling coefficient will not reverse [13].

Using an optical analog of the tight-binding (TB) model [21,22], we can extract the measured coupling factor κ as $|\kappa_a| = |\frac{\Delta\omega_a}{\Omega}| = |\frac{\omega_a^\pi - \omega_a^0}{\Omega}|$ for the antisymmetric stacking configuration. After substituting $\omega_a^0 = 2.18$ GHz, $\omega_a^\pi = 1.51$ GHz, and $\Omega = 1.82$ GHz, we can obtain that $\kappa_a = -0.37$. Similarly, we can obtain the coupling factor for the symmetric stacking configuration as $\kappa_s = -0.13$. It is evident that the antisymmetric coupling configuration has a larger total coupling strength. Note that the coupling factors achieved from experimental measurement ($\kappa_a = -0.37$ and $\kappa_s = -0.13$) are almost the same with the coupling factors obtained from the Lagrangian analytical model ($\kappa_a = -|\kappa_{Ha} + \kappa_{Ea}| = -0.38$ and $\kappa_s = -|\kappa_{Hs} - \kappa_{Es}| = -0.15$).

When the number of vertically stacked magnetic MSSs is increased, a waveguide transmission band can be expected due to the vertical coupling of individual resonant modes, similar to previous coupled resonator optical waveguides (CROWs) [21]. Note that previous CROWs were predominantly based

FIG. 5. (a) Dispersion diagrams of two infinite chains of metallic spiral structures with symmetric (blue line) and antisymmetric (red line) stacking configurations. (b) Measured transmission spectra (S parameters S_{21}) for two finite vertical magnetic-coupled resonator waveguides which consist of nine MSSs separated with 6-mm-thick foam plates with symmetric (blue line) and antisymmetric stacking configurations (red line). Bottom right inset shows the experimental setup. Upper left inset shows the scanned E_z field pattern at 1.8 GHz on top of the symmetric stacking waveguide.

on electric coupling or electric current exchange [11,12], but the CROW we will demonstrate here is magnetic-coupling dominant. The intrinsic dispersion relation of an infinite chain of vertically stacked magnetic MSSs can be obtained as $\omega_{s(a)} = \omega_0[1 + \kappa_{s(a)} \cos(Kh)]$ [21], where ω_0 is the resonance frequency of an individual MSS, $|\kappa_{s(a)}| = \frac{|\omega_{s(a)} - \omega_{s(a)}^+|}{\omega_0} = |\kappa_{Hs} - \kappa_{Es}|$ or $|\kappa_{Ha} + \kappa_{Ea}|$ is the inter-MSS coupling strength, K is the Bloch wave vector, and h is the periodicity of the vertical waveguide. We calculate dispersion curves of an infinite vertical chain of MSSs arrayed in both symmetric and antisymmetric configurations with periodicity $h = 6$ mm, as shown in Fig. 5(a). The magnetic localized surface plasmon modes are transported in the vertical waveguide in the frequency bands centered at the resonance frequency of an individual MSS (black dashed line). The waveguiding band of the antisymmetric stacking configuration (between upper cutoff frequency 2.5 GHz and lower cutoff frequency 1.15 GHz) is wider than that of the symmetric stacking configuration (between upper cutoff frequency 2 GHz and lower cutoff frequency 1.6 GHz), because of the larger coupling strength between neighboring MSSs in the antisymmetric stacking configuration.

To experimentally demonstrate the vertical transport of magnetic localized surface plasmons in deep-subwavelength scales, we constructed a vertical stacked CROW which consists of nine magnetic MSSs with periodicity of $h = 6.0$ mm, as shown in the bottom right inset of Fig. 5(b). The measured results are shown in Fig. 5(b). We first measured the transmission spectrum (gray triangles) without the CROW showing that EM energy cannot transport vertically in air at frequencies from 0.6 to 3 GHz. Then we measured the transmission spectra (S parameter S_{21}) of two vertical magnetic CROWs with symmetric stacking configuration

(blue squares) and antisymmetric stacking configuration (red circles), respectively. Each stacking configuration exhibits a transmission band. For the antisymmetric (symmetric) configuration the measured transmission band is 1.2–2.4 GHz (1.5–2 GHz), whose frequency range matches well with the calculated band structure. The measured field pattern of E_z at 1.8 GHz [upper-left inset of Fig. 5(b)] on the top surface of both symmetric and antisymmetric stacking configurations shows a clear magnetic dipole mode [18,19], showing that the mode profile is not changed during energy transport. We also simulated and illustrated the wave propagation along this CROW in Fig. S3 in the Supplemental Material [20].

IV. CONCLUSIONS

In conclusion, we have experimentally demonstrated a deep-subwavelength MSS dimer system in which the magnetic interaction dominates. A Lagrangian analytical model is adopted to analyze the coupling mechanism. Moreover, two deep-subwavelength vertically coupled magnetic resonator chains with two different stacking configurations are experimentally realized at microwave frequencies, whose energy transport follows the dispersions of CROW. This work applies an alternative type of magnetic “meta-atom” into metamaterial construction, and provides possibilities of magnetic metamaterial design in which the electric interaction no longer takes precedence.

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