

# Electrically small multiband antenna based on spoof localized surface plasmons

Rong Lin Shao<sup>1</sup>, Bo Li<sup>2</sup>, Liu Yang<sup>1</sup>, and Yong Jin Zhou<sup>1,3,\*</sup>

<sup>1</sup> Key Laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai 200444, PR China

<sup>2</sup> Kuang-Chi Institute of Advanced Technology, State Key Laboratory of Metamaterial Electromagnetic Modulation Technology, Shenzhen 518057, Guangdong, PR China

<sup>3</sup> State Key Laboratory of Transducer Technology, Chinese Academy of Sciences, Shanghai 200050, PR China

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**Abstract.** Here an electrically small multiband antenna based on spoof localized surface plasmons (LSPs) has been proposed using corrugated ring resonator printed on a thin dielectric substrate with complementary metallic spiral structure (MSS) on the ground plane. It has been found that the resonant frequencies of spoof LSPs redshift by tuning the arm length of the complementary MSS, which leads to the miniaturization of the antenna. The fabricated multiband antenna has a small size of only  $0.11\lambda \times 0.1\lambda$ , covering GSM900, GSM1800, and WiFi bands. Such electrically small multiband antenna with high gain is necessary for efficient wireless energy harvesting (WEH), which can find more applications in various areas including Internet of Things (IoT), wireless sensor network (WSN), etc.

**Keywords:** Localized surface plasmons / metamaterials / surface plasmons

Self-sustainable low-power electronic devices have attracted significant attention in the past few years, due to their wide applications in the Internet of Things (IoT), green cellular networks [1], and wireless sensor networks (WSNs) [2]. Nevertheless, it requires smaller and smaller nodes for comfortable user experience [2,3]. Smaller nodes imply smaller batteries, creating strict trade-offs between the consumed energy and the performance. The energy harvesting (EH) technologies provide a solution to replacing or recharging the battery [4]. Wireless energy harvesting (WEH) is one of the most favorable EH technologies for supplying continuous power to the self-sustainable stand-alone devices [2], which harvests the electromagnetic (EM) waves in the air. WEH has been applied to health monitoring sensors [5], structural health monitoring sensors [6], satellite health monitoring [7], RFID tags [8], biotelemetry communication [9], etc. Compared with the WEH systems with dedicated radio frequency (RF) sources in references [10–14], ambient EM signals in the air are normally available at low levels ( $-25$  to approximately  $-7$  dBm/m<sup>2</sup>) [15], distributed in multiple frequency

bands and random incident angles. To maximize the overall microwave-to-DC conversion efficiency, the designed rectenna should harvest ambient EM energy from different frequency bands simultaneously and the beam width should be wider. Besides, compared with the rectifier circuit, power management system and sensor modules, the size of antenna is too large [16], since the dimensions of conventional antennas are generally half wavelength.

Metamaterials are composed of subwavelength particles, which have been used to harvest EM energies in the microwaves regime, including a flower-like structure composed of four electrically small split-ring resonators (SRRs) [17], a circular slotted truncated corner square patch radiator placed on reactive impedance surface (RIS) [18], a parallel connection of five SRRs loaded with embedded devices [19], etc. However, previous designs focused on a single narrow frequency band and required a relatively high input power level. Loop antennas over artificial magnetic conductor surface for dual-band energy harvesting have been proposed [20]. But the antenna is not compact enough. Surface plasmons (SPs) are collective electron–photon oscillations tightly attached to the surface of a metal, which are characterized with subwavelength confinement and field enhancement [21]. SPs could be

\* Corresponding author: [yjzhou@shu.edu.cn](mailto:yjzhou@shu.edu.cn)



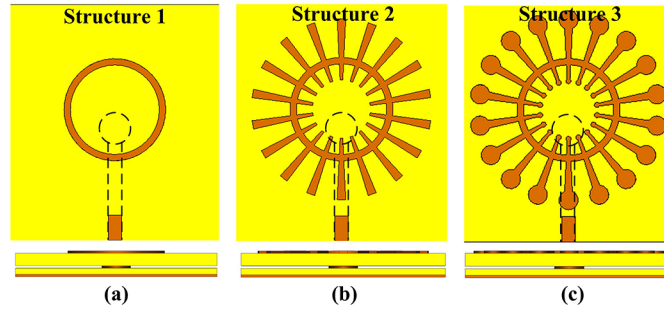


Fig. 2. The top view and side view of antennas based on (a) Structure 1, (b) Structure 2, and (c) Structure 3.

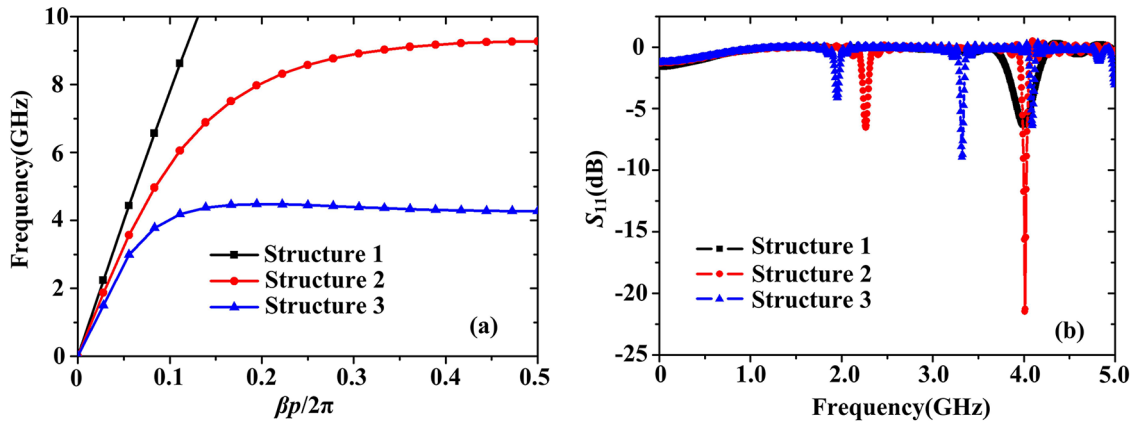


Fig. 3. (a) Dispersion curves and (b) simulated reflection coefficients of Structures 1–3.

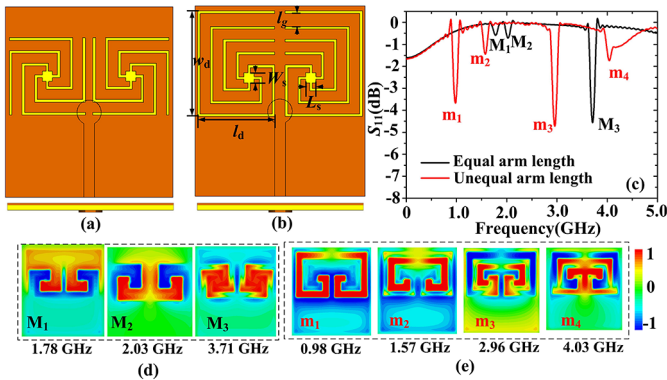
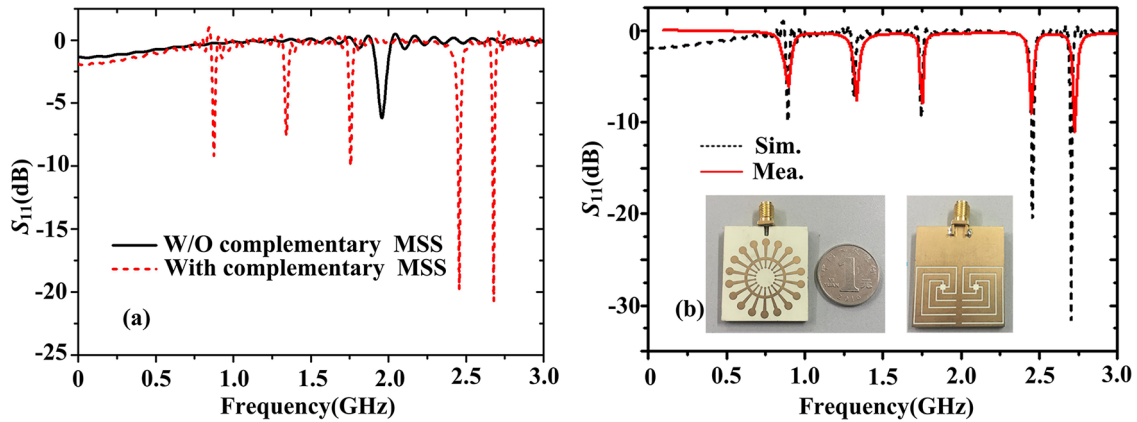


Fig. 4. Top view and side view of the complementary MSS with (a) equal arm length and (b) unequal arm length. (c) Simulated reflection coefficients of the complementary MSSs. (d) The simulated 2D  $E_z$ -field distributions on the plane located 1 mm above the complementary MSS with equal arm length. (e) The simulated 2D  $E_z$ -field distributions on the plane located 1 mm above the complementary MSS with unequal arm length.

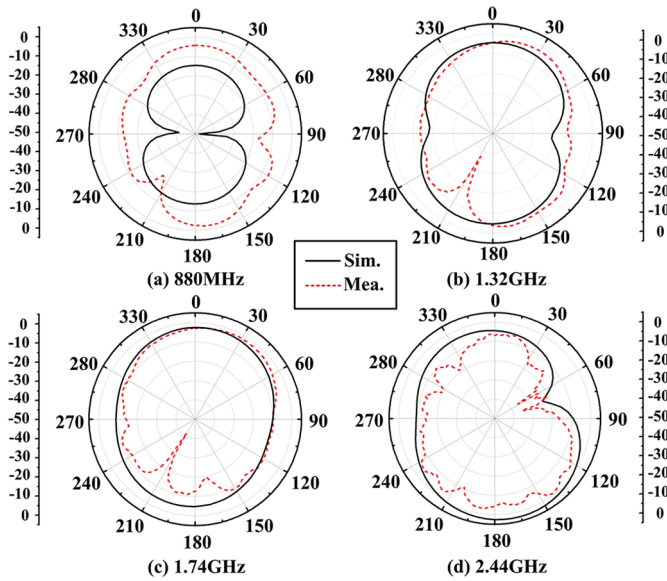
LSPs modes and the magnetic LSPs modes are suppressed. Next, we will investigate the effects of the complementary MSS by tuning the arm length. The electric field distributions are shown in Figure 4e, from which we can see that all of these modes are electric LSPs modes and the

magnetic LSPs modes are suppressed. For the lowest resonant mode ( $m_1$ ), the electric fields concentrate on the longest arm. For  $m_2$  mode, they concentrate on the second longest arms. For  $m_3$  mode, they concentrate on the second shortest arms. That is, by tuning the arm length, there would be more electric LSPs modes, which is beneficial to realize the multiband and miniaturization of the antenna.

Based on the above analysis, the complementary MSS with unequal arm length has been integrated with the corrugated ring to realize the antenna miniaturization. The proposed antenna radiates through the interaction of spoof LSPs and complementary MSSs, which can work at the lower frequencies, especially due to the introduction of the complementary MSSs. Figure 5a shows the simulated reflection coefficients of the antenna with and without the complementary MSS with unequal arm length. It shows that the antenna with the complementary MSS with unequal arm length exhibits resonances at 0.88, 1.32, 1.74, and 2.44 GHz. Comparing to the antenna without the complementary MSS with unequal arm length, the antenna can excite more resonant modes at lower frequencies, since the complementary MSS with unequal arm length etched on the ground plane can excite more spoof electric LSPs modes. The fabricated antenna is shown in the inset of Figure 5b and the simulated and measured  $|S_{11}|$  (reflection coefficients) is represented in Figure 5b. It shows that the measured and simulated reflection coefficients are in good agreements.



**Fig. 5.** (a) Simulated reflection coefficients of the antenna with and without the complementary MSS with unequal arm length. (b) Measured and simulated reflection coefficients of the fabricated antenna.



**Fig. 6.** Measured and simulated radiation patterns of proposed antenna.

Figure 6 gives the simulated and measured radiation patterns of the antenna at four different frequencies: 0.88, 1.32, 1.74, and 2.44 GHz, respectively. The measured gain are  $-1.53$  dBi at 0.88 GHz,  $-2.15$  dBi at 1.32 GHz,  $-2.00$  dBi at 1.74 GHz, and  $-2.58$  dBi at 2.44 GHz, respectively. Furthermore, it can be seen that the beamwidth of the proposed antenna is wide. There are some discrepancies between the measured and simulated results at the lowest frequency (880 MHz), which may come from the limitations of our microwave anechoic chamber that works above 900 MHz. The performances of the proposed antenna have been compared with other electrically small multiband antennas in Table 1. It can be observed that the proposed antenna shows smaller electrical size compared with other works in references [15,20].

In this paper, an electrically small multiband antenna based on spoof LSPs has been proposed, fabricated, and

**Table 1.** Comparison between ours and others' design.

Reference	Frequency (GHz)	Size (mm <sup>2</sup> )	Gain (dBi)
[15]	0.55–2.5	160 × 160	2.5–5
[20]	0.5, 0.875	500 × 500	8.2, 8.5
This work	0.88, 1.32, 1.74, 2.44	33 × 37	$-1.53$ , $-2.15$ , $-2.00$ , $-2.58$

analyzed, and the reduction of resonant frequencies has been explained by dispersion curves. Furthermore, the complementary MSS has been etched on the ground plane, which results in further reduction of the resonant frequencies and exciting more electrical spoof LSP modes at lower frequencies. The antenna also exhibits relatively high gain with a compact size ( $0.11\lambda \times 0.1\lambda$ ). These properties make the antenna suitable for WEH, IoT, and WSN applications.

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