A New Quad-band and Polarization-Insensitive Metasurface for RF Energy Harvesting and Its Design Optimization

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Abstract

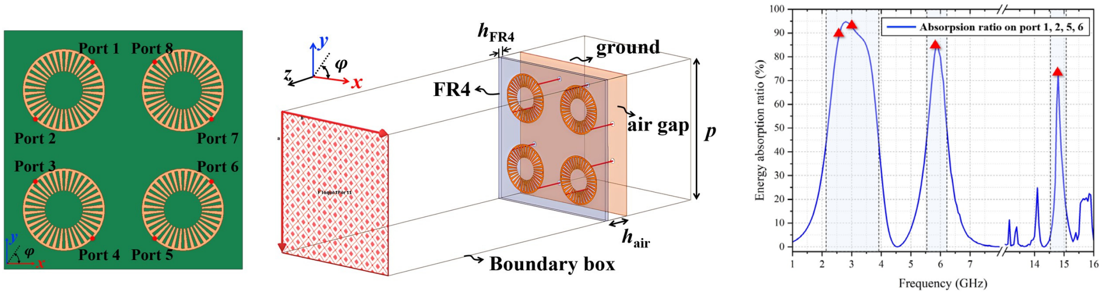
To address the inconvenience and the maintenance cost of conventional batteries in the development of large-scale low-power wireless sensors, radio frequency (RF) energy harvesting (EH) technology has gained significant tractions since RF energy offers advantages such as abundant availability and resilience to environmental conditions. In this study, we propose and optimize a novel topology for a quad-band and polarization-insensitive metasurface (MS) absorber. The MS unit employs four spoof-local-surface-plasmons (SLSPs) resonators arranged using a sequentially-rotation technique, enabling a polarization insensitivity and facilitating a post-stage power accumulation. We then develop an optimization methodology by combining a hybrid algorithm and finite element method simulations to calculate the performance parameters. The methodology is applied to a prototype design, demonstrating exceptional results.

1 Introduction

The proliferation of low-power electronic devices has increased the maintenance cost of the conventional battery power supply, making it impractical for emerging applications. Radio frequency (RF) energy harvesting (EH) technology offers a feasible solution due to the abundant ambient RF resources. However, there are still technical challenges in engineering RF energy harvesters. First, the low power density of ambient RF sources, scattered spectrum distribution and uncertain wave directions and polarization states require RFEH absorbers with a high conversion efficiency, a multi-band capability, a wide-angle coverage, and a polarization insensitivity. Second, RFEH absorbers are often arranged in arrays due to the minimal energy harvested by individual units, but the increasing number of ports and lumped elements in the array introduces additional losses which reduces the overall efficiency and complicates the design of the post-stage circuits. To address these challenges, this paper presents a novel metasurface (MS) absorber topology and its optimization methodology.

2 The MS Absorber and Its Design Optimization

A unit cell of MS absorber based on a subwavelength split ring resonator (SRR) structure was first proposed in [1], and different variants [2]-[3] were subsequently introduced for energy harvesting. Nevertheless, these prototype units either suffer from excessive lumped elements or working in an insufficient frequency band, and are also sensitive to the polarization direction. To resolve these problems, a new topology of a quad-band and polarization-insensitive MS absorber in considerations of RF power accumulations is proposed and optimized. Fig. 1 (a) shows the schematic configuration of the proposed MS unit cell, which consists of a top metal pattern, a FR4 dielectric layer, an air gap layer, and a metal ground. The air layer is introduced to reduce the effective dielectric permittivity to enhance the energy absorption bandwidth. The top metal pattern includes four spoof-local-surface-plasmons (SLSPs) resonators arranged using a sequentially-rotation technique [4], exhibiting deep subwavelength and multimode resonances. Symmetrical metal vias connect the resonators to the power output ports on the ground. The center-symmetric structure enables RF power accumulations, reducing port loss and enabling harvesting of arbitrary-



(a) (b)

Figure 1: (a) Schematic diagram of the proposed MS unit cell topology (φ is the angle between the direction of the electric field and the x-axis); (b) The optimized simulation ratio of power captured on ports 1, 2, 5, 6 when $\varphi = 45°$.

polarized incident waves. To achieve a high absorption efficiency simultaneously at four commonly-used RF bands: 2.45, 3, 5.85 and 14.85 (f_1 to f_4) GHz, a multi-objective minimization problem is formulated as

$$\min\{F(x)\} = \min\left\{-\lambda_1 \sum_{i=1}^{4} \beta_i F_{f_i}(x) + \lambda_2 \sum_{i=1}^{4} \beta_i L_{f_i}(x)\right\} \quad (1)$$

where F_{f_i} and L_{f_i} are the accumulation of the energy-absorption ratios and the accumulation of loss ratios of resistive port 1, 2, 5 and 6 at frequency f_i when $\varphi = 45°$. Parameters that have considerable influences on the performances of the MS absorber, the decision variable vector x, including the resistance of each port (R_{port}), the radius of the outer ring (r_1) and the central hollow circle (r_2), the periodic side length (p), the height of the air gap (h_{air}) and the FR4 layer (h_{FR4}), is optimized. To solve the multimodal optimization problem of (1), an optimization methodology combining a hybrid algorithm and finite element method simulations is proposed and employed.

3 Numerical results and conclusions

To validate the performance of the proposed MS absorber, a prototype absorber is initialized and then optimized using the proposed optimization methodology. The MS array is modeled and simulated using the finite element method by implementing excitations of Floquet ports and enforcing periodic boundary conditions in the full-wave electromagnetic simulation. A hybrid algorithm combining PSO and fireworks algorithm to enrich the population diversity and enhance the convergence speed is developed to solve the corresponding optimization problem, and will be explained in details in the full paper. As shown in Fig. 1 (b), the proposed MS unit achieves very high radiation-to-ac conversion efficiencies of 90% , 94% , 89% , and 74% with minimal dielectric losses at the four desired frequency bands. In addition, based on the sequentially-rotation characteristics, the topology could harvest incoming waves with arbitrary polarizations and is favorable for power accumulations, making it a competitive candidate in RFEH applications.

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