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Gain enhancement of transmitting antenna incorporated with double-cross-shaped electromagnetic metamaterial for wireless power transmission

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ABSTRACT

This paper proposes a novel approach to enhance the aperture efficiency of the transmitting microstrip patch antenna (MPA) by designing a new inclusion of double-cross-shaped metamaterial (DCSM) superstrate applied in microwave wireless power transmission(WPT). Overall WPT model and transmitting antenna selection are briefly introduced and numerical simulation is conducted in HFSS. Homogenization retrieval method based on transmission and reflection coefficients is utilized to calculate the effective parameters of the DCSM unit cell, electric field and surface current distribution are displayed to qualitatively explain the occurrence of negative permittivity and permeability. The Matlab2008a script is also presented to calculate the geometry dimensions of the corresponding conventional patch antenna operating at desired resonant frequency. Simulation results indicate that the gain of the transmitting antenna increases from 7.46 dB to 12.35 dB after loading with the $6 \times 3 \times 1$ array DCSM MTM as the superstrate, the measured gain increases from 7.1 dB to 12.21 dB thus an enhancement of 184% for the transmitting antenna's aperture efficiency is obtained which is of significant value for the whole WPT system. For the last section of our paper, electric field of the transmitting MPA before and after loading with DCSM superstrate are illustrated to gain insight physical mechanism of the gain enhancement.

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1. Introduction

The idea of transmitting electrical energy without any medium from the supply terminal to stationary or relatively movable load, namely wireless power transmission or wireless power transfer, was initially proposed by Nikola Tesla as early as in 1904 [1]. He carried out the first experiment involving wireless power transmission via the electrical field by constructing the huge Tesla Coil on his Wardenclyffe Tower Facility, but finally failed indeed because the energy transmitted was diffused

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in all directions and no data were collected on whether any significant amount of power would be available at any distant point in Colorado Springs. Several decades later, the attempt to transmit power via microwave beams was suggested by Peter Glaser in 1964 in the well-known SPS (Solar Power Satellite) project, in which huge amount of renewable and clean solar energy are envisaged to transmit as a microwave beam to the ground station with stringent safety continuously [2]. He also demonstrated in another subsequent research program that a microwave powered helicopter flown for ten hours at an altitude of 50 feet. The helicopter was equipped with a device called a rectenna, which was sustained solely by a 2.45 GHz microwave beam [3]. During the 1980s and early 1990s, a program called SHARP(Stationary High Altitude Relay Platform) was developed to build the first unmanned airplane,flying around a stationary point at the altitude of 22Km,whose energy refueling was planted to be implemented by means of a 2.45 GHz microwave beam transmitted from ground and received on board by a rectenna [4]. In 2007, the resonant coupling experiment conducted by Marin Soljacic and his colleagues in MIT garnered much attention around the world. A 60w light bulb attached to the received coil was lit successfully 2 m away from another transmitting coupling coil [5]. This work has since inspired many other researchers towards the more detailed understanding and wider application of the resonant coupling WPT. One year later, the Hawaii WPT experiment by John Mankins of Managed Energy Technologies set a new distance record in the long-distance WPT research [6]. The distance between the transmitting point to the receiving one is 148 km, but the received power was less than 1% of the transmitted power.

The applications of wireless power transmission span over a broad range from portable consumer electronics to powering electric vehicles, as well as pervasively charging sensor or implantable biomedical devices. Generally speaking, wireless power transmission can be classified in the following four categories: inductive coupling [7], resonant coupling [8], microwave [9] and laser [10]. It is well-known that the transfer mechanism of inductive coupling can only take effect within the distance of few centimeters and its power transfer efficiency decrease with distance [7]. The disadvantage of the resonant coupling method is that the two resonant objects aimed to exchange power energy have to be tuned to resonate at the same frequency and it needs very big transfer device if we want the whole system to work in low frequency bands [8]. For short range applications where the transfer distance varies from a few centimeters to a few meters, the near-field inductive coupling or resonant coupling is feasible, but isn't a viable solution to provide high transfer efficiency for energy transfer over a mid-range or long distance. Therefore, it is worthwhile to gain more attention in mid-range or long-distance wireless power transmission system. Laser owns the advantage of having small beam divergence, but the efficiency in generating the laser beam and converting it back into electrical energy are low compared with the microwave method [10]. The microwave method is the most suitable WPT for applications from mid-range to long-distance transmission with high efficiency.

Metamaterials are artificial engineered materials composed of periodic subwavelength particles and exhibit exotic electromagnetic properties which are extensively studied in recent decades [11–16]. The metamaterial is also referred as left-handed material as the vectors E, H and k form a left-handed-like set of systems. In the field of WPT, the MTMs are also reported to increase the efficiency in literatures. However, to the best of the authors' knowledge, the majority of contemporary WPT schemes applied the MTM into the short distance near-field inducting coupling or resonant coupling system to achieve high transfer efficiency over short distance [17–19]. The metamaterial slab was usually positioned between the transmitting and receiving coils by focusing the propagating waves and enhancing the near-field evanescent waves. In many cases, however, the space between the coils may not be accessible to incorporate a metamaterial slab. Therefore, further investigation of the MTM based WPT method using a different approach is necessary.

In this paper, distinguished from the aforementioned methods, we present the inclusion of double-cross-shaped metamaterial to enhance the aperture efficiency of the transmitting antenna as its superstrate in the mid-range or long-distance WPT system. Compared with the conventional microstrip patch antenna(MPA) which is selected as the transmitting antenna, the DCSM loaded MPA had higher gain and became more directive. The DCSM supertrate can converge the radiation width in the space and reduce half-power width through the suppression of surface wave energy radiation. In the condition that the transmitted power is fixed, the receiving antenna can collect more received power for the transmitting MPA with DCSM loading as its supertrate compared to the case without the DCSM loading. Moreover, this inclusion design can also help reduce the area of the corresponding receiving rectenna array and thus decrease the profile of the whole WPT system.

2. Overall WPT model and transmitting antenna

The overall wireless power transmission model mainly consists of the transmitting-receiving-rectifying system as is illustrated in Fig. 1 [20]. The transmitting antenna in the transmitting system is a device which converts the electrical power into plane electromagnetic waves in free space. The receiving system is built mainly for receiving the transmitted microwave power and removing the harmonics presented in received waves. The rectifying system is the main apparatus of transforming the microwave to direct current. As the most significantly important element of the transmitting system, a high-efficiency transmitting antenna is desirable for the whole WPT transmitting system due to its capability of acting as a radio wave transmitter. A number of works have dealt with the efficiency enhancement for the receiving system and rectifying system, the research for the transmitting antenna is still quite limited for the mid-range or long-distance WPT system.

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