Linear-Polarization-Insensitive Rectenna Design for Ground-to-Air Microwave Power Transmission

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ABSTRACT This paper presents a linear-polarization-insensitive rectenna for the ground-to-air microwave power transmission (MPT). With an integration of a hybrid coupler and a dual-linearly-polarized (DLP) antenna, a linearly-polarized (LP) incident wave can be decomposed by the antenna polarization tilts into the horizontally-polarized (HP) and the vertically-polarized (VP) components, correspondingly, which are then distributed evenly through the hybrid coupler as the inputs of two successive lumped rectifiers. Thus, RF-to-dc power conversion efficiencies (PCEs) of the presented DLP rectenna maintain insensitive to its incident LP polarization tilts. An aperture-coupled feeding mechanism and lumped matching networks are employed to enable the compact DLP rectenna design for practicality. Both theoretical analysis and experimental results validate that the RF-to-dc PCEs of the DLP rectenna keeps stable high regardless of its LP polarization tilts, which demonstrates a prospect for the ground-to-air MPT applications.

INDEX TERMS Dual-linearly-polarized (DLP) antenna, linearly-polarized (LP) wave, hybrid coupler, rectifier, microwave power transmission (MPT).

I. INTRODUCTION

The ground-to-air microwave power transmission (MPT) has gained increasingly attention as it can continuously supply dc power to an unmanned aerial vehicle (UAV) [1]–[3] shown in Fig. 1, where RF-to-dc power conversion efficiency (PCE) of an onboard rectenna is commonly a critical concern [4], [5]. Therefore, to maintain its high RF-to-dc PCEs under various circumstances has become a hot research focus recently.

As demonstrated by the ground-to-air MPT system in Fig. 1, radar sensing technology has been successfully implemented to find and track a UAV target, then dynamically to control beams of transmitting (TX) antenna (array) adaptive to a receiving (RX) antenna (array) to retain a maximum wireless power link [6], [7]. Though the radar sensing can mitigate an antenna radiation direction misalignment, it is still difficult to always maintain a polarization alignment between TX/RX antennas, which causes serious polarization mismatch loss in wireless power link and deteriorates the RF-to-dc PCEs of an onboard rectenna of whole ground-to-air MPT system.

Some recent researches have been reported to overcome the problems of the antenna polarization misalignments [8]–[13]. The work in [8] presents a circularly-polarized (CP) rectenna for a linearly-polarized (LP) wave receiving.
However, 3-dB polarization mismatch loss always happens, which degrades the maximum wireless power link between TX/RX antennas. In [9]–[11], it demonstrates that a dual-linearly-polarized (DLP) antenna can receive all incidence for the two successive sub-rectifiers with parallel dc combinations. Accordingly, RF-to-dc PCEs can be relatively sustained regardless of the antenna polarization tilts. The microwave power distribution scheme [9]–[11] can be typically modeled as demonstrated by Fig. 2a. Though the DLP antenna can be utilized to receive all power of an LP incident wave by decomposing incidences into the horizontally-polarized (HP) and the vertically-polarized (VP) components, the received power distributions \( P_{\text{HP}} \) and \( P_{\text{VP}} \) at the HP and VP ports of the DLP antenna are not always even, which degrades the RF-to-dc PCE when combining uneven dc voltages from two sub-rectifiers (i.e., rectifier1, 2 in Fig. 2a).

To redistribute uneven power of \( P_{\text{HP}} \) and \( P_{\text{VP}} \), a hybrid coupler is introduced between the DLP antenna and sub-rectifiers [12], [13], whose microwave power distribution scheme is shown in Fig. 2b. It is indicated that the hybrid coupler redistributes the uneven \( P_{\text{HP}} \) and \( P_{\text{VP}} \) with even magnitudes for two successive sub-rectifiers (i.e., rectifier1, 2 in Fig. 2b), which accordingly maintains more robust RF-to-dc PCEs of the DLP rectennas than those (Fig. 2a) [9]–[11] when an antenna polarization tilt happens. To some content, the DLP rectenna in Fig. 2b is the best candidate for a polarization-insensitive MPT application. However, it is not effective for all polarization scenarios, e.g., elliptical or circular polarization, etc. Hence, besides the LP incidence, another complex polarized wave is also analyzed, which offers a wise guide for what scenarios should this LP-insensitive rectenna (Fig. 2b) be implemented by avoiding its RF-to-dc PCE deteriorations. Additionally, to develop more practical DLP rectenna according to the microwave power distribution scheme shown in Fig. 2b, two sub-rectifiers with lumped matchings are employed for the compact rectenna realization, which leaves spaces for further implementation of a power management or some other functional electronics, e.g., a microcontroller unit (MCU) [14] and a dc-to-dc bulk converter [15]. Moreover, the aperture-coupled mechanism [16]–[18] is introduced to design the shared-aperture DLP antenna, which isolates the feeding layer and radiating patch by an air gap without any mutual interaction. Due to the air gap in between, high gains of the presented DLP antenna can be achieved. On the basis of the shared-aperture DLP and the two lumped rectifiers, an LP-insensitive DLP rectenna can be realized by integrating the hybrid coupler. Both theoretical analysis and experimental results validate that the RF-to-dc PCEs of the DLP rectenna maintains stable high regardless of its LP polarization tilts, which demonstrates a prospect for the future ground-to-air MPT applications.

II. THEORY ANALYSIS AND OPERATION MECHANISM
In this section, an LP incident wave is firstly analyzed, which validates that the proposed LP-insensitive rectenna can receive all incidences and redistribute uneven \( P_{\text{HP}} \) and \( P_{\text{VP}} \) evenly for two successive sub-rectifiers without polarization mismatch loss. However, the polarization of an incident wave refers to the orientation of the electric field vector, which may change with time instead of LP fixed direction. Consequently, other complex polarized wave is selected for the effectiveness analysis of microwave power distribution scheme in Fig. 2a.

A. LINEARLY-POLARIZED INCIDENT WAVE ANALYSIS
As illustrated in Fig. 3a, an LP incident wave travels along the \( \hat{z} \) direction. \( \varphi \) is a polarization tilt between the \( \hat{y} \) direction and the incident electric field vector (see Fig. 3b).

\[
\vec{E} = E_1 \hat{x} + E_2 \hat{y} \\
\varphi = \tan^{-1} \frac{E_1}{E_2} \\
E_0^2 = E_1^2 + E_2^2
\]  

(1)  
(2)

where \( E_1 \) and \( E_2 \) are the electric field magnitudes along \( \hat{x} \) and \( \hat{y} \) directions, \( E_0 \) is constant unaffected by polarization tilts \( \varphi \). Thus, the corresponding voltages (i.e., \( V_{\text{HP}} \) and \( V_{\text{VP}} \)) at HP and VP ports of the DLP antenna can be approximated as follows.

\[
V_{\text{HP}} = \epsilon E_1 \hat{x} \cos \varphi \\
V_{\text{VP}} = \epsilon E_2 \hat{y} \cos \varphi
\]  

(3)  
(4)

where \( \epsilon \) is constant determined by DLP antenna performance. Subsequently, the entire power (i.e., \( P_t \)) received by the DLP antenna can be calculated with a summation of \( P_{\text{HP}} \) and \( P_{\text{VP}} \) at the HP and VP ports based on (3, 4).

\[
P_t = P_{\text{HP}} + P_{\text{VP}} = \frac{\epsilon^2 E_1^2}{2Z_0} + \frac{\epsilon^2 E_2^2}{2Z_0} = \frac{\epsilon^2 E_0^2}{2Z_0}
\]  

(5)
where \( Z_0 \) is the antenna port impedance, typically \( Z_0 = 50 \Omega \). It is demonstrated that all the LP incident power is received by the HP and VP ports irrespective of DLP antenna polarization tilt angle \( \varphi \). However, it suffers an uneven-power-distribution problem as shown in (3, 4) when \( \varphi \) deviates from 45° and 135°, which can degrade the RF-to-dc PCEs of two successive sub-rectifiers with dc combination (see Fig. 2a). To redistribute the uneven \( P_{\text{HP}} \) and \( P_{\text{VP}} \), a hybrid coupler is introduced to enable an uneven-to-even microwave distribution scheme as given in Fig. 2b. It is capable of evenly redistributing LP incident wave from its input port \( (P_1) \) to the direct \( (P_2) \) and coupled \( (P_3) \) ports with 90° phase difference while the isolation port \( (P_4) \) is highly isolated. The four-port S-parameter can be derived by the odd-even mode theory [19], which can be expressed as follows.

\[
S = \begin{bmatrix}
0 & -i & -1 & 0 \\
-i & 0 & 0 & -1 \\
-1 & 0 & 0 & -1 \\
0 & -1 & -i & 0 \\
\end{bmatrix}
\]  

(6)

When \( P_1 \) and \( P_4 \) of the hybrid coupler are connected to the HP and VP ports of DLP antenna, the uneven power distributions from (3, 4) can be redistributed evenly to \( P_2 \) and \( P_3 \) based on the above S-parameter and the corresponding port voltages are calculated with (7, 8).

\[
V_{\text{dir}} = -\frac{(iV_{\text{HP}} + V_{\text{VP}})}{\sqrt{2}} = -\frac{(iE_1 \hat{x} + E_2 \hat{y}) \cos \varphi}{\sqrt{2}}
\]  

(7)

\[
V_{\text{cou}} = -\frac{(iV_{\text{VP}} + V_{\text{HP}})}{\sqrt{2}} = -\frac{(iE_2 \hat{y} + E_1 \hat{x}) \cos \varphi}{\sqrt{2}}
\]  

(8)

Consequently, the even power redistributions at the direct and coupled ports can be calculated as follows.

\[
P_{\text{dir}} = \frac{e^2 E_1^2}{4Z_0} + \frac{e^2 E_2^2}{4Z_0} = \frac{e^2 E_0^2}{4Z_0}
\]  

(9)

\[
P_{\text{cou}} = \frac{e^2 E_2^2}{4Z_0} + \frac{e^2 E_1^2}{4Z_0} = \frac{e^2 E_0^2}{4Z_0}
\]  

(10)

It indicates \( P_{\text{dir}} \) and \( P_{\text{cou}} \) preserve even insensitive to LP tilts, which enables the maximum RF-to-dc PCEs of two successive sub-rectifiers with dc combination as demonstrated in Fig. 2b.

### B. OTHER COMPLEX POLARIZED WAVE ANALYSIS

Different from LP incidences, the polarization of an incident wave may change with time. Thus, to conduct the analysis of another complex polarized wave, the electric field vector by the DLP antenna can be assumed with

\[
\vec{E'} = (E'_1 \hat{x} + iE'_2 \hat{y}) \cos \varphi
\]  

(11)

Therefore, the corresponding port voltages of the DLP antenna can then be modified from (3, 4) to (12, 13).

\[
V'_{\text{HP}} = \varepsilon E'_1 \hat{x} \cos \varphi
\]  

(12)

\[ V'_{\text{VP}} = iE'_2 \hat{y} \cos \varphi \]  

(13)

The entire power \( iP' \) received by the DLP antenna can be calculated with a summation of \( P'_{\text{HP}} \) and \( P'_{\text{VP}} \) at the HP and VP ports according to (12, 13).

\[
P'_{\text{HP}} = P'_{\text{HP}} + P'_{\text{VP}} = \frac{e^2 E_1^2}{2Z_0} + \frac{e^2 E_2^2}{2Z_0} = \frac{e^2 E_0^2}{2Z_0}
\]  

(14)

where \( E_0^2 = E_1^2 + E_2^2 \) is constant unaffected by polarization tilts. Though entire power of another complex polarized wave can still be captured by the DLP antenna, the hybrid coupler in Fig. 2b cannot operate effectively to realize uneven-to-even power distributions. According to the S-parameter in (6), the corresponding port voltages are calculated with (15, 16).

\[
V'_{\text{dir}} = -\frac{(iV'_{\text{HP}} + V'_{\text{VP}})}{\sqrt{2}} = -\frac{i(E'_1 \hat{x} + E'_2 \hat{y}) \cos \varphi}{\sqrt{2}}
\]  

(15)

\[
V'_{\text{cou}} = -\frac{(iV'_{\text{VP}} + V'_{\text{HP}})}{\sqrt{2}} = -\frac{(E'_1 \hat{y} - E'_2 \hat{x}) \cos \varphi}{\sqrt{2}}
\]  

(16)

Therefore, the power redistributions at the direct and coupled ports of the hybrid coupler can be calculated as follows.

\[
P'_{\text{dir}} = \frac{e^2 (E'_1 + E'_2)^2}{4Z_0}
\]  

(17)

\[
P'_{\text{cou}} = \frac{e^2 (E'_1 - E'_2)^2}{4Z_0}
\]  

(18)

It demonstrates that the power magnitudes of (17, 18) cannot keep even if \( E'_1 = 0 \) or \( E'_2 = 0 \), which is not suitable for maximum RF-to-dc PCEs of two successive sub-rectifiers. Consequently, only the LP incidence is effective for the proposed microwave power distribution scheme as given in Fig. 2b.

### III. RECTENNA DESIGN AND EXPERIMENTAL RESULT

To enable the DLP antenna with compact configuration, the aperture-coupled mechanism [16]–[18] is adopted, which can isolate radiating patch and feeding layer by an air gap. Due to the introduced air gap in between, high antenna gains can be achieved. Consequently, the LP-insensitive rectenna can be realized with an integration of the shared-aperture DLP antenna, two lumped rectifiers, and the hybrid coupler for the ground-to-air MPT applications.

#### A. SHARED-APERTURE DLP ANTENNA

The shared-aperture DLP antenna at 2.45 GHz is designed in Fig. 4, which consists of two substrate layers (20-mil-thick Rogers RO4350B with \( \varepsilon_r = 3.66, \tan \delta = 0.0031 \)). The detailed parameters of the DLP antenna are provided in TABLE I as follows.

As illustrated in Fig. 4b, the feeding layer is located on the backside of the second substrate. Two H-shape slots on the ground layer (i.e., GND in Fig. 4b) are carefully optimized together with some other parameters (e.g., feeding layer, air gap, and radiation patch size, etc.) in the CST Studio Suite. Hence, the feeding layer provides a strong coupling through
TABLE 1. Detailed parameters of DLP antenna design.

| $L_s$ | $L_F$ | $s$  | $t$  | $S_{1,1}$ | $S_{1,2}$ | $S_{1,3}$ |
|------|------|------|------|---------|---------|---------|
| 70 mm | 47.2 mm | 4 mm | 0.508 mm | 8 mm | 2.2 mm | 10 mm |
| $S_{2,1}$ | $L_1$ | $L_2$ | $L_3$ | $w$ | $d$ | $d_1$ |
| 0.2 mm | 23 mm | 12.1 mm | 11.46 mm | 1.1 mm | 13 mm | 45° |

**FIGURE 4.** Configuration of DLP antenna design. (a) Exploded view. (b) Side view. (c) GND layer. (d) Feeding layer.

The simulated and measured $S$-parameters of DLP antenna are given in Fig. 5a. There is a good agreement between the simulation and measurement. The reflection coefficient less than $-10$ dB at HP and VP ports can be enabled from 2.38 to 2.52 GHz and 2.38 to 2.5 GHz, respectively. Moreover, the simulated and measured isolation between the two ports is achieved below $-20$ dB within the frequency range from 2.38 to 2.52 GHz. The simulated peak gains at 2.45 GHz at HP and VP ports can both achieve the maximum values (> 8 dBi). The gain difference between two input ports is negligible, which shows a benefit for the LP incident wave decomposing.

### B. LUMPED RECTIFIER DESIGN

To realize a compact rectenna, two identical lumped rectifiers operating at 2.45 GHz are designed and optimized in advanced design system (ADS) by harmonic balanced (HB) simulation. The 7th-order of HB is selected to ensure enough high accuracy. The values of the input matching network ($L_{m}$ and $C_{m}$) are co-optimized together with the connection 50-Ω microstrips (20-mil-thick Rogers RO4350B), which helps to be integrated with the shared-aperture DLP antenna as given in Fig. 4. The lumped circuit schematic and its photograph are illustrated in Fig. 6a. During the lumped rectifier designs, low-threshold HSMS2860 [20] diodes are implemented to achieve high RF-to-dc PCEs over power range of interest (from 2 to 12 dBm). Murata capacitor of $C_{m} = 1$ pF and inductor of $L_{m} = 2.2$ nH are implemented to enable a maximum power incidence. Additionally, Murata capacitor of $C_{L} = 22$ μF and resistor of $R_{L} = 980$ Ω are employed as a low pass filter for the maximum dc power extraction. By measuring the output dc voltages ($V_o$) on the resistive load ($R_L$), the RF-to-dc PCE of the lumped rectifier can be calculated with

$$\eta = \frac{V_o^2}{R_L} \times \frac{1}{P_{in}} \times 100\%$$  \hspace{1cm} (19)

Fig. 6b shows the simulated and measured RF-to-dc PCEs and output dc voltage ($V_o$) of the designed lumped rectifiers. It can be observed that a good agreement between the simulation and measurement is achieved. The RF-to-dc PCE is higher than 50% over an incident power range of approximately 2 to 12 dBm, which helps to enable high-efficiency MPT with an integration of the DLP antenna and a common-used hybrid coupler.

**FIGURE 6.** Lumped rectifier design. (a) Schematic and layout of lumped rectifier. (b) Simulation and measurement (i.e., scatter) of $V_o$ and PCEs.

### C. INTEGRATION OF DLP ANTENNA, RECTIFIERS AND HYBRID COUPLER

To realize the integration with the shared-aperture antenna and the two lumped rectifiers, a common-used hybrid coupler [19] is implemented by using same 20-mil-thick Rogers RO4350B. As demonstrated in Fig. 7a, the microstrip lines
on the feeding layer are combined with the input ($P_1$) and isolation ($P_4$) ports of the hybrid coupler. However, it should be noticed that the connection microstrips ($l_{f1} = 10.43$ mm, $l_{f2} = 15.64$ mm) between the slots and margin of hybrid coupler should be long enough to avoid antenna performance deterioration.

D. EXPERIMENTAL VALIDATION

The measurement setup is presented in Fig. 8a to validate the proposed LP-insensitive DLP rectenna. An incident power of 20 dBm is generated by the signal generator AV1441A, which interrogates VP port of the designed DLP antenna (see Fig. 4). Another DLP rectenna is located away from the DLP antenna with a distance of $d$ (30, 40, 50, 60 cm), which means different incident power for two sub-rectifiers [21]. When carrying out LP-polarization-insensitive experiments, the tilt angle of DLP rectenna rotates from 0° to 90° with an angle step of 15°, and the output voltages ($V_o$) are then measured as demonstrated.

Since the air gap in between the two substrates are utilized, the frequency bandwidth and antenna gains are thus enhanced. To evaluate the effective frequency bandwidth of DLP rectenna, the frequency of the signal generators is tuned from 2.35 to 2.50 GHz with a step of 0.05 GHz, whose LP-insensitive experimental validation results under various distances ($d$) are provided in Fig. 9.

It is indicated that with an increase of the tilt angles, the output voltages ($V_o$) perform a robustness, which validates the LP-insensitive capability. The ripples may come from the uneven radiation gains of the different oriented direction. Additionally, the maximum dc output voltage happens when the operation frequency is 2.45 GHz. Even a little degradation occurs when frequency varies from 2.35 to 2.50 GHz, the high performance of the proposed DLP rectenna still maintains.

IV. CONCLUSION

This paper presents an LP-insensitive rectenna for ground-to-air MPT. With an integration of the DLP antenna, two lumped rectifiers and hybrid coupler, LP incidence can be decomposed by the antenna polarization tilts into HP and VP components, respectively, and then redistributed evenly through the hybrid coupler as the inputs of the two successive lumped rectifiers. Consequently, the RF-to-dc PCEs of DLP rectenna maintain insensitive to its incident LP polarization tilts. Besides the LP incidence, other complex polarized wave is analyzed, which offers a wise guide for what scenarios should this proposed LP-insensitive rectenna be implemented by avoiding the RF-to-dc PCE deteriorations. Moreover, two sub-rectifiers with the lumped matchings are introduced for a compact rectenna design, which leaves spaces for further functional electronics implementation. Additionally, aperture-coupled mechanism is introduced to design the shared-aperture DLP antenna, which isolates the feeding layer and radiating patch by an air gap to enhance the frequency bandwidth and antenna gains. Furthermore, the rectenna sizes should be carefully tuned to its half wavelength correspondingly for an array facilitation. Both theoretical analysis and experimental results validate that the RF-to-dc PCEs of the DLP rectenna preserves stable high regardless of its LP polarization tilts, which demonstrates a prospect for the future ground-to-air MPT applications.

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