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DC-pass filter design with notch filters superposition for CPW rectenna at low power level

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Abstract. In this paper the challenging coplanar waveguide direct current (DC) pass filter is designed, analysed, fabricated and measured. As the ground plane and the conductive line are etched on the same plane, this technology allows the connection of series and shunt elements to the active devices without via holes through the substrate. Indeed, this study presents the first step in the optimization of a complete rectenna in coplanar waveguide (CPW) technology: key element of a radio frequency (RF) energy harvesting system. The measurement of the proposed filter shows good performance in the rejection of $F_0=2.45$ GHz and $F_1=4.9$ GHz. Additionally, a harmonic balance (HB) simulation of the complete rectenna is performed and shows a maximum RF-to-DC conversion efficiency of 37% with the studied DC-pass filter for an input power of 10 μ W at 2.45 GHz.

1. Introduction

Energy harvesting has been the center of attention recently with the development of Internet of Things [1]. Energy can be harvested from different sources, such as the sun, the wind, vibration and electromagnetic waves. Moreover, with the increase of wireless data transfer in our environment, electromagnetic energy can be considered as a source of energy. This energy could be collected and used to power small devices, such as sensors [2]. This is achieved, using rectenna (Figure 1.a). One of the challenges relies on the repeatability of their conception. Specifically the repeatability of vias needed to connect surface mounted component (SMC) to the ground. Rectenna realizations should be robust to improve repeatability. This is important, because energy harvesting often requires complex rectenna or more than one rectenna due to the low level power of available electromagnetic energy. Hence, antenna array or rectenna array are used to provide higher voltage to power the storage energy unit or the device itself. The first solution is convenient when dealing with simple structure and mono frequency antenna. But, as the complexity of antenna and number of frequency increase, one has to deal with phases shifting and complex matching impedance circuitry. The second solution, rectenna array, avoids those problems by combining the DC voltage of several rectenna. However, this method requires many vias in microstrip technology that can lead to performance shifting in rectenna [3].

This work is dedicated to the second possibility. To limit risks of frequency shifting or performances degradation, we avoid the use of vias. To achieve this, we use coplanar waveguide (CPW) (Figure 1.b) instead of microstrip. As the ground plane and the conductive line are etched on the same plane, drills in the substrate are no longer required. The topic of this paper focuses on the design and conception of an easy-to-build, compact and uniplanar DC-pass filter for CPW rectenna.



First, two discrete-element notch filters are simulated and their equivalent circuits in CPW technology are conceived and tuned with Momentum in Agilent ADS software. Then, a DC-pass filter is realized by superposition of the two notch filters.

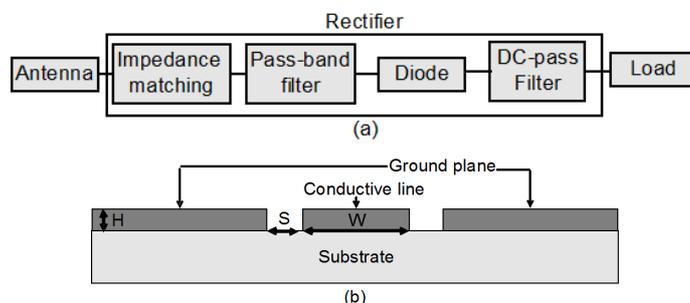


Figure 1. Synoptic of a rectenna(a) and CPW structure (b)

2. DC-pass filter design

To improve rectifying efficiency, one must ensure proper DC voltage to the load. This can be achieved by using a parallel capacitor as DC-pass filter after the rectifying process of the diode. In the literature, the equivalent model of a parallel capacitor in CPW can be modeled by an open-end coplanar shunt stub in the ground plane [4]. But, this solution cannot be used in our rectenna conception because it implies the use of an air bridge to ensure equality of the potential ground. Indeed when a discontinuity is etched in the CPW circuitry, the propagation of the parasitic coupled slot line mode should be considered.

The investigation of other filters leads to the following structure: instead of the well-known parallel capacitor, a series inductance or a resonant structure can act as a DC-pass filter.

Subsequently to this work, our final objective is to realize via-less rectenna working in the ISM band, and precisely at $F_0=2.45$ GHz to use in a direct RF source feeding scheme. In rectenna circuits, rectifying process of the diode generate higher order harmonics ($F_0, F_1=4.9$ GHz, etc) in addition to the DC. To achieve higher conversion efficiency, those harmonics must be cancelled out from the DC output. Working at low input power level, we considered the effects of higher order harmonics superior to F_1 negligible. Hence, the conception of only two notch filters is performed at F_0 and F_1 , which in this case when combined together act as a DC-pass filter.

2.1. 2.45-GHz and 4.9-GHz notch filter

The first proposed filter is realized with a series short stub in the conductive line on AD1000 substrate, with $\epsilon_r=10.35$, substrate height $h=0.762$ mm and dielectric loss $\delta=0,002$. The stub length value, $L_{s0}=12.48$ mm, is obtained through tuning using Momentum simulator. Concerning the etching process steps, all the CPW notch filter slots have been done with the same width for simplicity ($S=0.7874$ mm). Hence, the conductive line width $W=3.7$ mm to obtain a characteristic impedance line of 50Ω . This structure does not introduce any gap in the conductive line, so the DC part of the signal can reach the load. The simulated planar filter S-parameters and the discrete-element equivalent circuit are plotted in Figure 2.

Using the same principle, a second resonant structure is designed in order to reject the first higher order harmonic at $F_1=4.9$ GHz corresponding to L_{s1} (Figure 2.b). This structure is represented in CPW by a series stub in the conductive line with length $L_{s1}=5.98$ mm.

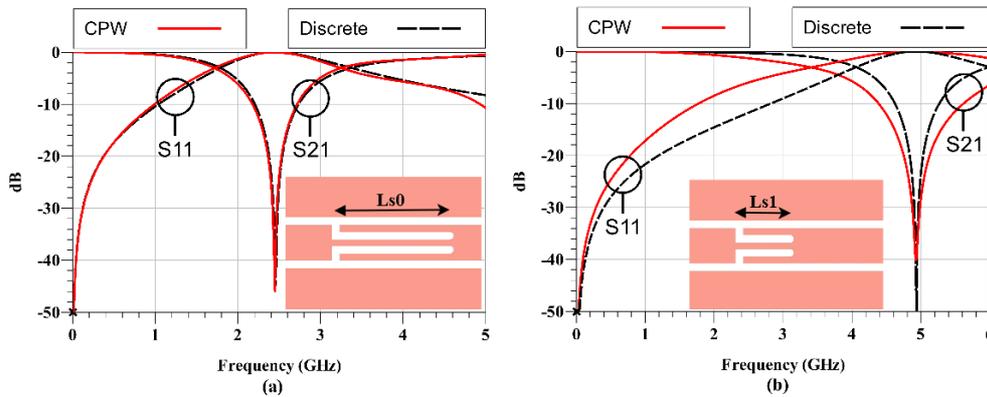


Figure 2. S-parameters of the discrete-element and CPW simulated 2.45-GHz notch filter (a) and 4.9-GHz notch filter (b) with their respective layout representation.

2.2. The complete DC-pass filter

Both of the two notch filters are etched on the conductive line of the CPW structure. In order to create the DC-pass filter, the two frequencies must be filtered. One could combine them in series to achieve the global DC-pass filter. But, this type of combination increases the size of the global DC-pass filter. Another solution when realizing CPW stub in series, is to etch the stub in the ground plane, which shows similarity with defected ground structure (DGS). But, by etching the stub in the ground plane, the bandwidth is narrowed for the chosen frequency, leading to better quality factor. In our study, we know that the first higher order is predominant over the second one in the output signal. Consequently, the 2.45-GHz notch filter was chosen to be milled on the ground plane with a new slightly modified value, $Ls0'=13.5$ mm. Using the superposition principle, both filters are etched in parallel on the same board (Figure 3).

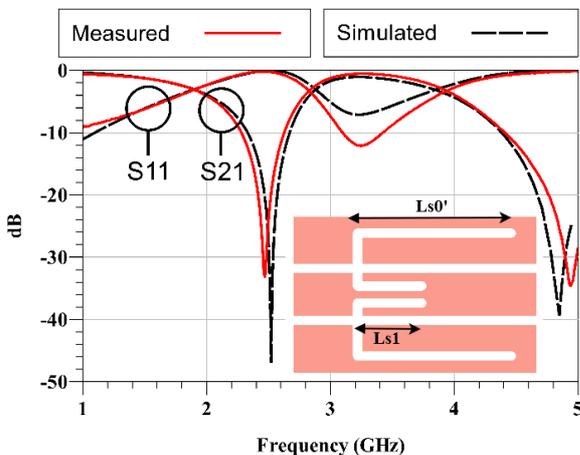


Figure 3. S-parameters of the measured and simulated proposed DC-pass filter with a layout representation

3. Measurement and application

The proposed DC-pass filter has been fabricated and measured (Figure 3). The measured and simulated results show good agreements. But a frequency shift is observable in Figure 3. We believe this shift is explained by the milling process and the precision in substrate dielectric value $\Delta\epsilon_r = \pm 0.35$.

Subsequently to this work, a first rectenna (Figure 4) using the proposed DC-pass filter and a discrete-element matching circuit, has been simulated with ADS. The S1P (1-port) block represents the S parameters of a CPW dipole antenna and the S3P (3-ports) block allows the separation of the injected power and the reflected power. The matching circuit is composed of an inductance $L4=9.9$ nH and a capacitor $C5=5.2$ pF. Results shows a rectifying efficiency up to 37% at 2.45 GHz for $P_{in}=-20$ dBm (Figure 5).

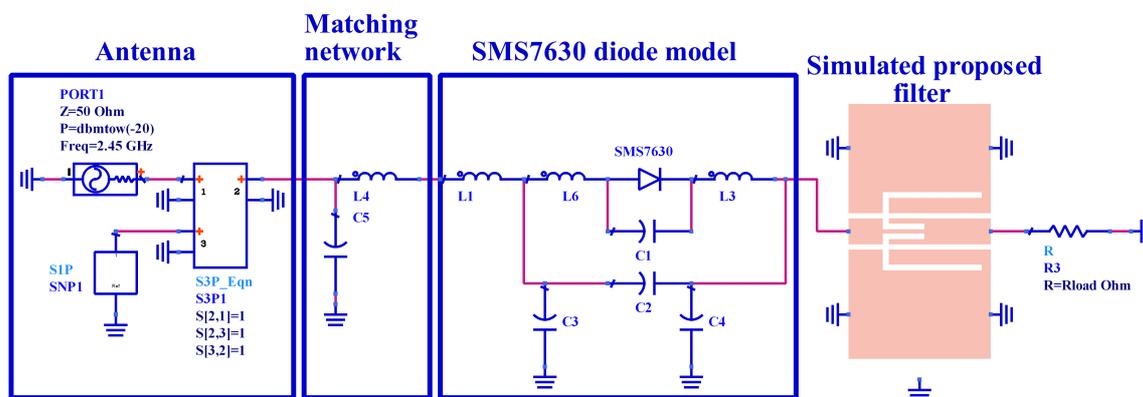


Figure 4. Schematic view of the simulated rectenna at -20 dBm, 2.45 GHz and a load $R=5400 \Omega$

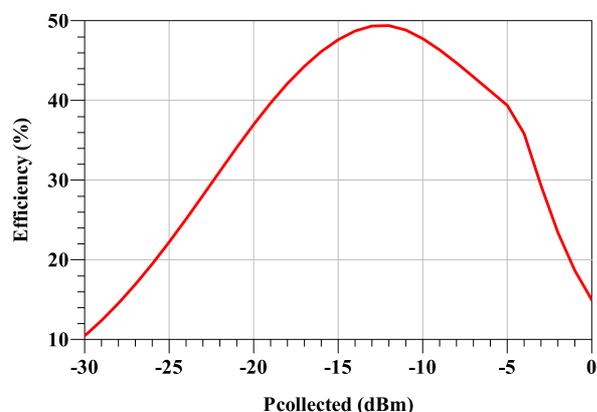


Figure 5. RF-to-DC conversion efficiency of the simulated rectenna with the proposed DC-pass filter.

4. Conclusion

In this paper, using the superposition of two notch filters, a DC-pass filter with multiple stop bands was realized and characterized on CPW. We showed that the prediction of the notch filters is possible with a simple resonant LC model. The Momentum simulations and measurements of the DC-pass filter showed good agreements. Thanks to the CPW physical structure, this DC-pass filter is suitable for a via-less rectenna design and its principle was demonstrated within a rectenna simulation.

Acknowledgments

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