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A Plasmonic Monopole Antenna Array on Flexible Photovoltaic Panels for Further Use of the Green Energy Harvesting

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Abstract—Due to urgent needs for exploring new energy resources, a novel approach is developed in this paper to integrate the functions of a photovoltaic (PV) panel with an ultra-wide band (UWB) antenna array as a unit for collecting solar energy and RF radiation power. The UWB antenna is printed on the front panel of the PV surface. The antenna structure is customized with minimum shadowing effects on the PV surface, by using eight monopoles connected to one SMA port as a single antenna array. Then, to ensure the bandwidth enhancement, each monopole is coupled to three Split Ring Resonators (SRR) structured in a single column as a matching circuit. Next, an experimental study is performed to investigate the amount of the harvested energy from both the PV and the antenna array. The antenna experimental measurements are conducted to realize the I-V characteristics for the PV and produced output voltage and efficiency from the RF radiation power at 900 MHz only. Numerically, the proposed antenna array performance is simulated by CST MWS and HFSS software packages. Finally, the antenna performance in terms of S_{11} and the radiation pattern at 900 MHz are measured and compared to the simulated results to end up with excellent agreements.

1. INTRODUCTION

Plasmonic phenomena have received considerable attention from many scientific research communities [1]. Recently, plasmonic effects have been applied in many applications including green energy harvesting such as thermal and solar energies as in [2]. For example, in [3–5], the application of thermos-plasmonic in membrane energy process was discussed. Nevertheless, such a technology led to design efficient Terahertz detectors with a thermoelectric response [6]. Such phenomena can be characterized by edge or surface-states, i.e., the electrons move along the surface of plasmonic structures instead of their inside [7]. Moreover, these plasmonic structures have been applied recently in wireless communication systems.

The early definition of wireless power transmission portrays is a unit that emits electrical power from one place and captures it in another place in the Earth's atmosphere without the use of wires or any other supporting medium [8]. The history of RF power harvesting in free space originated in the late of 1950s with a microwave-powered helicopter system [9]. Later, the concept of power harvesting was explained as a technique for retrieving the energy from the external environment [10] using different resources. This technique promises tremendous scope for the replacement of small batteries in low power electrical devices and systems [10].

Green energy harvesting technologies grow rabidly due to their massive potential for increasing batteries lifespans in different low-power sensor nodes and portable devices [11]. In general, most rechargeable batteries have short lifespans and require periodic replacements. Therefore, using power harvesting technologies may increase the lifespan of operation batteries. Green energy sources are available in different forms, such as solar power [12], wind energy [13], thermal energy [14],

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electromagnetic energy [15], and kinetic energy [16]. However, electromagnetic energy is unbounded and comes from different sources in which it is harvested without limitations.

RF energy harvesting systems receive and convert the RF energy into a DC voltage using antennas and rectifiers, respectively. Therefore, applying RF energy harvesting helps to reduce the dependency on batteries, which ultimately has a positive impact on green environment. RF harvesting process limits pollution with a clean energy source. Moreover, the RF energy availability with respect to the thermal or kinetic energy is not limited by the space or time. RF energy is available indoors, outdoors, rural and urban environments through the entire day. In spite of low power density, a deliberate source can be conducted for more efficient power transmission, and an enhanced circuit can be built to suit the load requirements. Such a feature promoted the research to realize RF harvesting in different applications such as wireless sensor networks and internet of things.

A novel approach is proposed in this paper to use the function of a PV panel for solar energy harvesting with a UWB antenna array to gather the RF power in a single structure. In Section 2 of the paper, the SRR structures based on the PV panel with all geometrical details are presented. The performance of the UWB antenna based on the antenna array in terms of S_{11} and gain spectra are evaluated in Section 3. In Section 4, the I-V characteristic of the conducted PV panel as the antenna substrate is measured with and without the array structure. Moreover, the collected RF energy at 900 MHz is measured experimentally to study the amount of produced output voltage and the efficiency. Finally, we conclude the paper in Section 5.

2. SRR GEOMETRICAL DETAILS

A classical circular SRR geometry is deposited on a flexible PV panel made of a polycrystalline silicon substrate. The SRR is considered in the antenna design to enhance the antenna bandwidth and gain as will be shown later in Section 3. Inside the substrate, the PV bus-bar is impeded and constructed from conductive silver strips. The relative permittivity of the substrate is $\varepsilon_r = 3.5$, and the loss tangent is $\tan\delta = 0.004$ [17]. The PV substrate thickness is 0.5 mm. The SRR usually shows a complex effective permeability of $\mu_{reff} = \mu_r' - j\mu_r''$ that follows Lorenzo distribution within the frequency band of interest [18]. However, due to the insertion of the bus-bar that is impeded inside the substrate, an effective permittivity component may appear as $\varepsilon_{reff} = \varepsilon_r' - j\varepsilon_r''$ at certain bands [19].

In this paper, the most popular circular SRR is considered, see Fig. 1, with two concentric splitted circles. The outer circle diameter is 40 mm with a strip width of 2 mm and splitted from the top with 2 mm gap. On the other hand, the internal circle diameter is 32 mm and the width of the strip is 2 mm

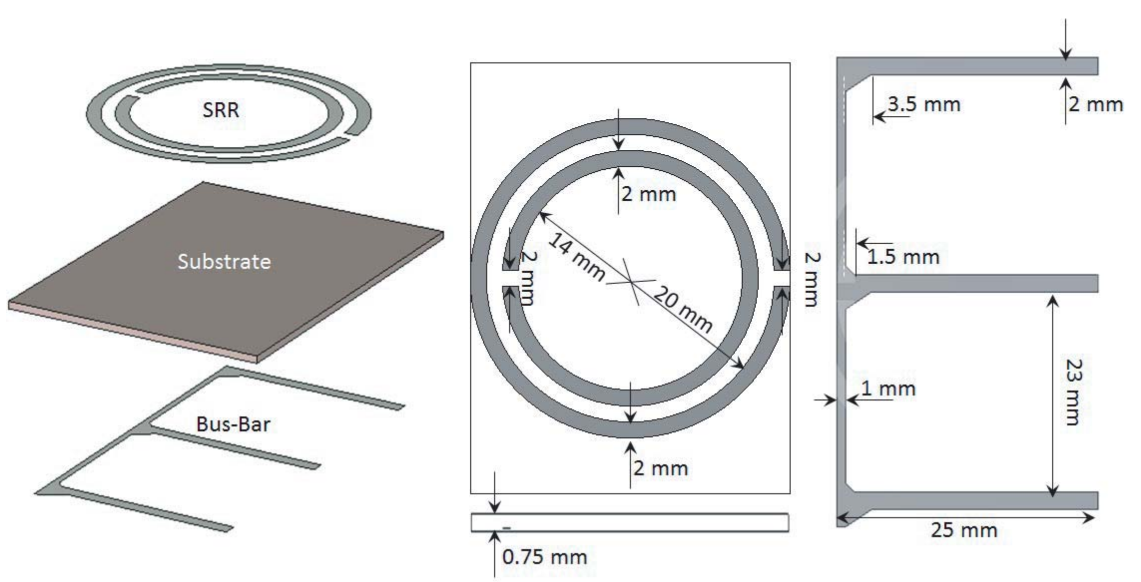

Figure 1. The geometrical details of the proposed SRR.

with a gap of 2 mm from the bottom. The outer and internal circles are mounted on the same substrate side. Nevertheless, the PV bus-bar is located underneath the SRR with a distance of 0.25 mm.

The proposed unit cell is characterized inside a factious waveguide, using CST MWS environments [20], to compute the S-parameters. Such computation is performed by conducting electric wells normally to the applied electric field and magnetic wells normally to the magnetic field that mimics the transverse electromagnet modes [21]. Two waveguide ports are applied to the ends of the waveguide.

Next, the constitutive electromagnetic parameters, ε_r and μ_r, of the proposed SRR with and without introducing the PV bus-bar structure are evaluated numerically as seen in Fig. 2. It is found that the proposed structure shows a significant change in the magnitude of ε_r and μ_r, see Fig. 2(b), after introducing the bas-bur structure in comparison to the original SRR without the PV bus-bar as demonstrated in Fig. 2(b).

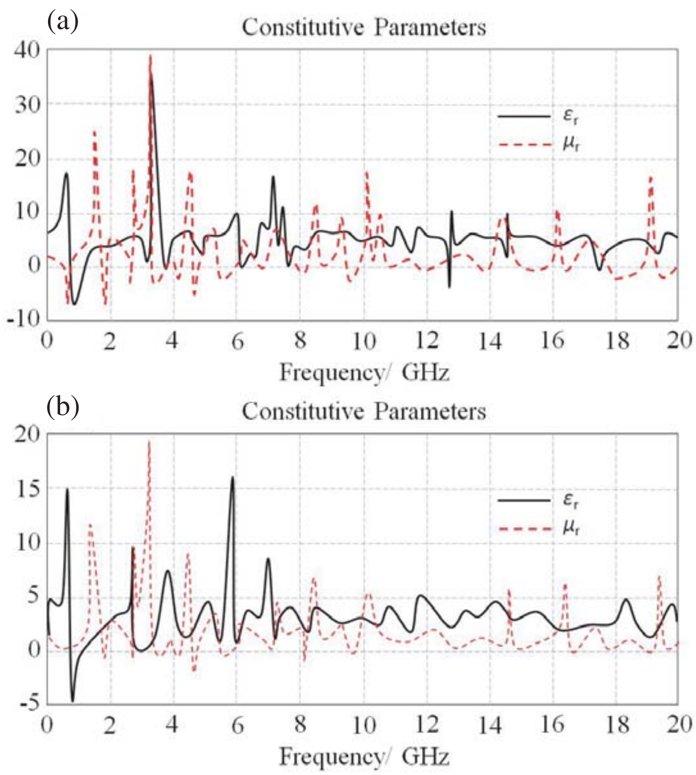

Figure 2. The evaluated ε_r and μ_r of the proposed SRR: (a) Without bus-bar and (b) with bus-bar.

Now, the dispersion properties of the proposed unit cell are tested inside the CST MWS environments to find the band gap location in the First Brillion Zone (FBZ) [22]. The unit cell is surrounded with perfect boundary conditions and perfect matching layer from the top. It is found from the presented results of the dispersion diagram in Fig. 3 that the major band gap around 1 GHz before introducing the bus-bar structure, however, after introducing the band gap a frequency shift is taken place when a significant reduction in the band gap is observed. This band gap is due to the location of the plasmonic effects of the SRR and the bas-bar structures.

3. ANTENNA GEOMETRY AND SIMULATION RESULTS

The antenna geometry based on a single monopole element is presented in Fig. 4(a). The antenna array constructed from 8 monopole elements is shown in Fig. 4(b). Each element is fed by a $\lambda/4$-transformer as seen in Fig. 4(c). The antenna array is mounted on the flexible PV panel, see Fig. 4(d), to be fed with a 50 Ω coaxial port. Each monopole element is attached to three SRRs for bandwidth enhancement.

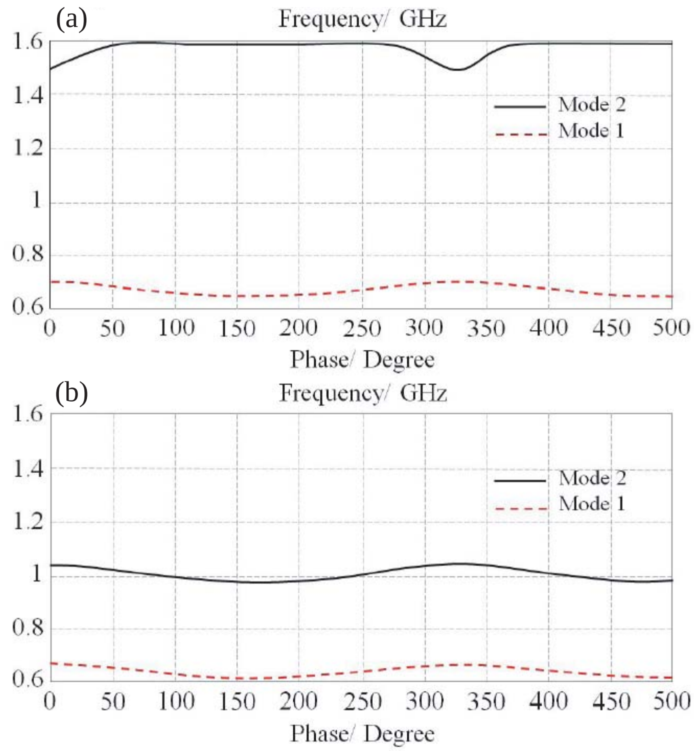

Figure 3. The evaluated dispersion diagram of the proposed SRR: (a) Without bus-bar and (b) with bus-bar.

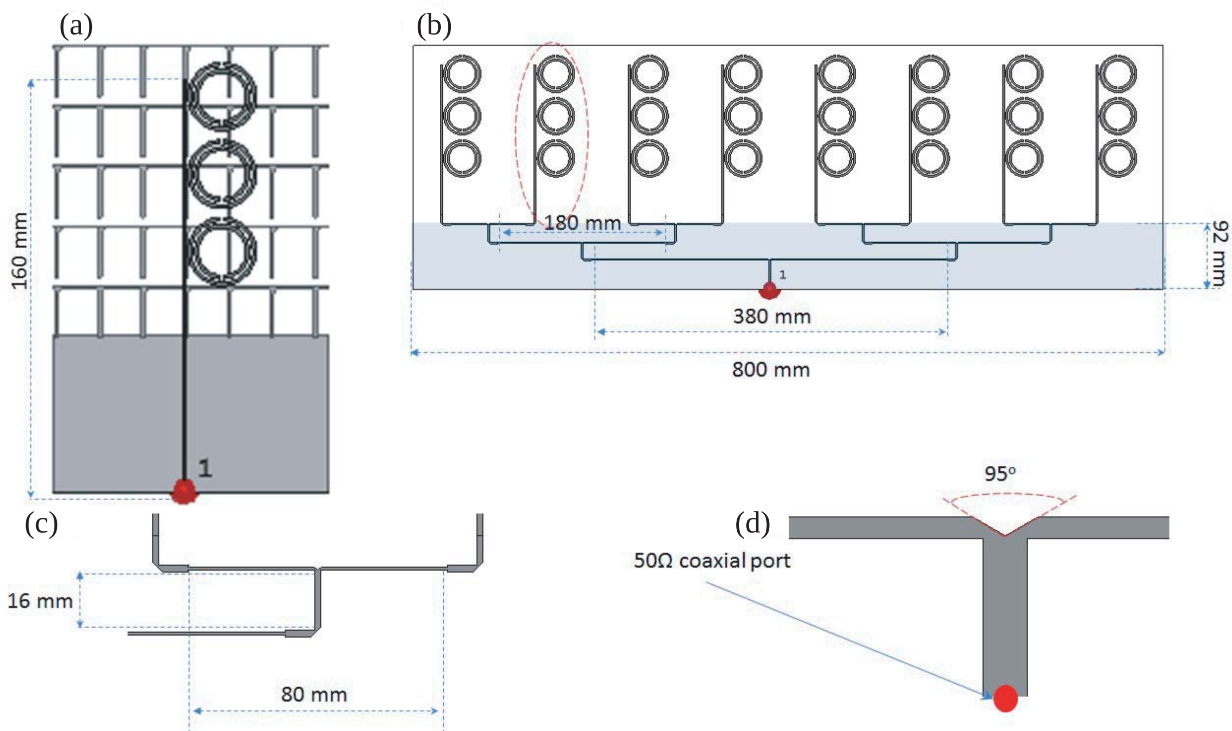

Figure 4. The proposed antenna structure; (a) single element, (b) array, (c) transmission line, and (d) discrete coaxial probe fee.

Based on numerical simulations, a parametric study is conducted to evaluate the effect of introducing the SRR rows as: single row, two rows, and three rows, consequently, on the S_{11} spectra as in Fig. 5. It is found that the bandwidth of the proposed antenna array increases significantly with increasing the number of rows, where the matching impedance of the antenna increases due to the effects of coupling between the monopole elements and the SRRs. Nevertheless, the antenna gain, generally, increases with increasing the number of SRR rows.

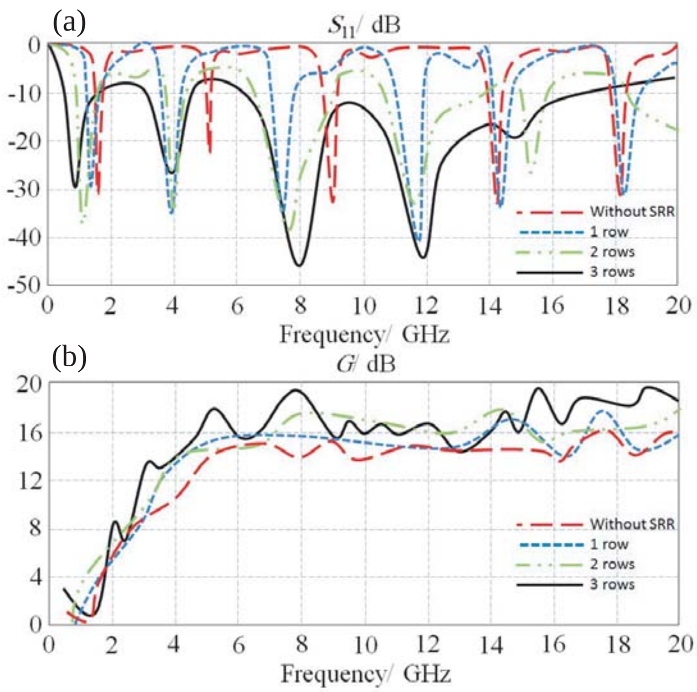

Figure 5. The simulated S_{11} and gain spectra of the proposed antenna with different number of the SRR rows.

Then, the HFSS software package based on FEM is used for validation [23]. The evaluated results in terms of S_{11} and gain spectra are presented in Figs. 6(a) and 6(b), respectively. It is found that the proposed antenna array shows a major bandwidth from 6 GHz up to 16 GHz with an acceptable gain varied from 15 dBi up to 19 dBi. The results from HFSS simulations are found in excellent match with CST MWS simulation results.

4. MEASUREMENT PROCESS AND SETUPS

4.1. Solar Energy Harvesting

The produced output voltage from the PV panel substrate before and after introducing the antenna structure is measured and presented as I-V characteristics in Fig. 7. The measurement is conducted in the outdoor sunny day environments with a voltage step of 1.5 volts. It is found that the maximum produced current is about 880 mA when the voltage is minimum about 0.1 volts. On the other hand, when the voltage is maximum, 14 volts, it is found that the current equals 178 mA. Later on, the same measurement is performed after introducing the proposed antenna array to find insignificant change in the produced current as can be seen in Fig. 7. Therefore, the aim of the proposed antenna array to minimize the shadowing effects has been demonstrated.

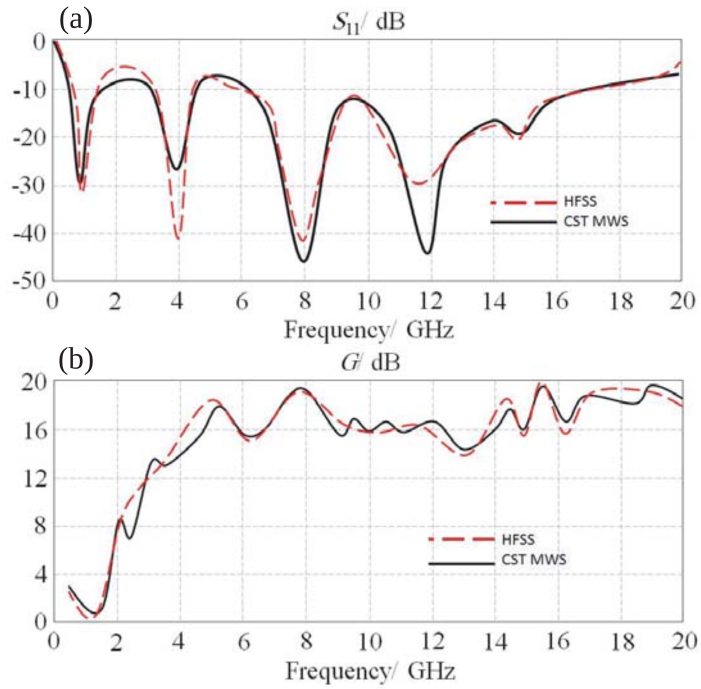

Figure 6. The numerical simulation results of the antenna array: (a) S_{11} and (b) gain spectra.

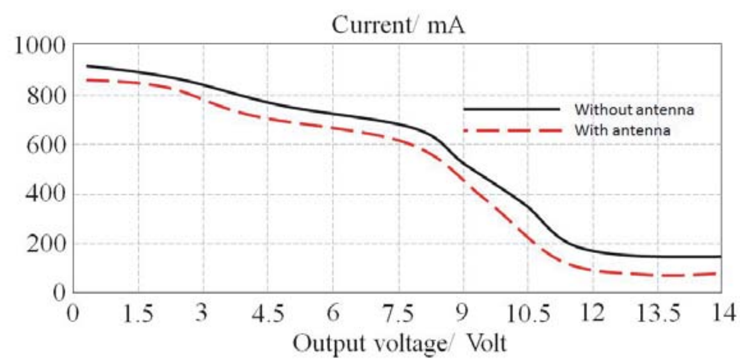

Figure 7. I-V characteristics measurements.

4.2. RF Energy Harvesting

The proposed antenna array is connected to an energy conversion module of 7 stages HSMS-2850 Schottky diode voltage doubler circuit at 900 MHz to convert the collected RF signals into DC voltage. The circuit design is based on the Villard voltage doubler circuit [24]. Nevertheless, an HSMS 2860 Schottky diode chip is introduced to match between the antenna load and the circuit rectifier impedance. The measurement setup is constructed based on a stander horn antenna operating around 900 MHz with a bore-sight gain of 8 dBi as seen in Fig. 8. The measurement is conducted inside a regular room with a distance of 10 m between the proposed antenna and the stander horn antenna.

The output SMA port is connected to a digital oscilloscope to measure the output voltage as seen in Fig. 9(a) with respect to the amount of the transmitted power from the horn antenna source. Next, the percentage efficiency is calculated relative to received RF power on the antenna with respect to the converted DC power as seen in Fig. 9(b). These measurements are performed at 900 MHz, because such a signal is the most available one in the space due to the GSM mobile communication network [25].

Figure 8. The measurement setup including the horn antenna, the proposed antenna array and the VNA pictures.

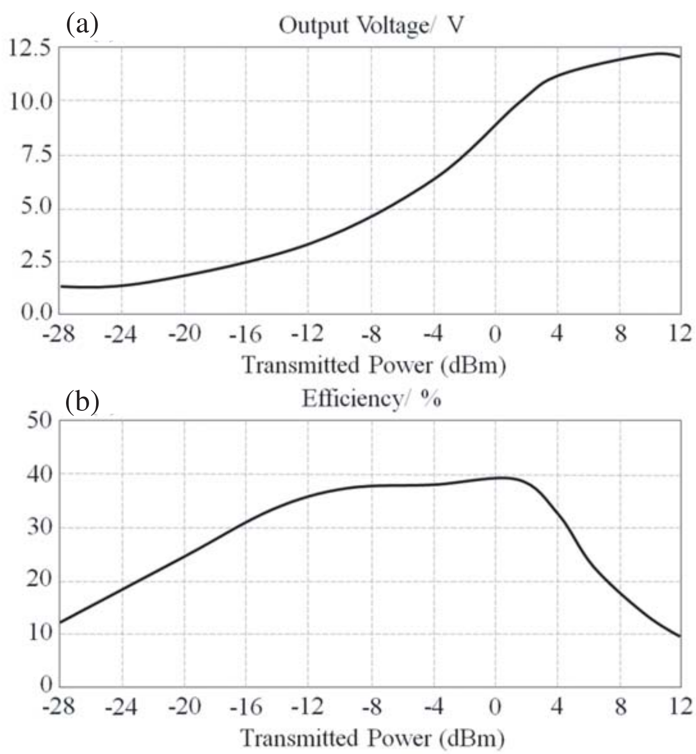

Figure 9. The measured results: (a) Output voltage and (b) efficiency.

Nevertheless, the proposed antenna array shows a plasmonic resonance at 900 MHz, in which the mutual coupling effects decay significantly [7].

The reason of using the RF convertor is to rectify the received energy in a DC voltage that can be used as a battery charger for different applications. On top of that, such a circuit shows an interesting feature when the seven stages are connected in series, in which it behaves like the principle of in series stacking batteries to get more voltage at the output.

4.3. Antenna Performance Measurements

Now, the antenna S_{11} spectra are measured before and after introducing the RF converter circuit, then, compared to each other as seen in Fig. 10(a). It is found that the antenna shows excellent matching at 900 MHz before introducing the RF convertor. Later on, the RF convertor is introduced to the antenna structure to measure the S_{11} spectrum. It is found that the frequency resonance is tuned slightly from 815 MHz to 929 MHz due to the effects of the RF convertor structure. However, the antennas in the two cases, before and after introducing the RF circuit convertor, are excellently matched. The antenna radiation pattern at 900 MHz only is measured inside an RF anechoic chamber as seen in Fig. 10(b). It is found that the proposed antenna provides a gain of 3.5 dBi.

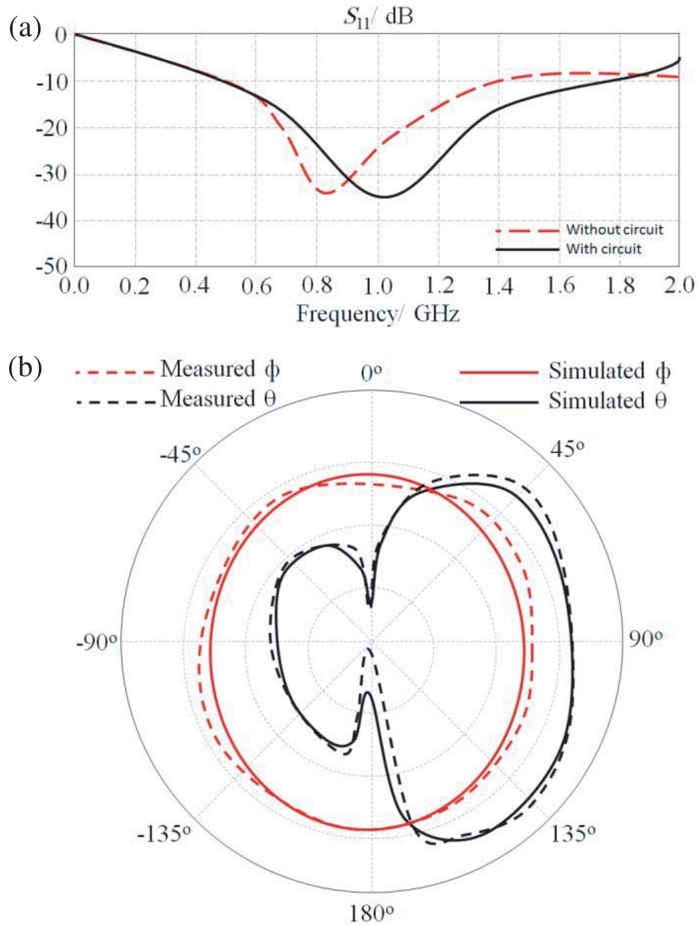

Figure 10. S_{11} measurements before and after attaching the RF circuit convertor: (a) S_{11} spectra and (b) radiation patterns.

5. CONCLUSION

In this paper, the green energy harvesting from both solar and RF power resources is demonstrated. The antenna array is constructed from 8 monopoles of copper layer printed on a flexible PV panel. The antenna elements are fed by a $\lambda/4$ network to be matched to a $50\,\Omega$ source. Nevertheless, a planner array of SRRs is mounted on the PV panel in adjacent to the antenna elements. Hence, a UWB is achieved, and the radiation pattern properties are enhanced to support the RF signals received from different frequency bands and directions. The antenna gain and S_{11} spectra are simulated numerically by two different software packages and compared for validations. From the obtained results, it is found that the antenna shows UWB with excellent gain. The experimental measurements are extended to evaluate the effects of adding the antenna structure on the produced current from the PV panel. When the solar panel is exposed to the sun light before and after introducing the antenna structure, insignificant effects are found on the generated I-V characteristics due to the small shadowing area of such an antenna structure. Then, the produced voltage from the RF energy is measured at 900 MHz at different transmitted power values from a horn antenna. The receiving efficiency is also characterized, and it is found that the maximum receiving efficiency is about 40%. The S_{11} spectra, before and after attaching the RF convertor circuit, are measured and compared to each other. A tuning effect, which is not effective, is observed due to the effects of the circuit structure introduction to the antenna array. Finally, the antenna radiation pattern at 900 MHz is measured and the gain found about 3.5 dBi.

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