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An Inkjet-Printed Ambient RF Energy Harvester

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Abstract:

Energy harvesting is a technology for extracting a minute amounts of power from ambient sources to typically supply low-power electronic circuits. In this proposed paper a low-cost energy harvester is presented, that uses RF energy sources. An antenna with a voltage doubler is used to convert the low input power to sufficiently high voltage levels for directly driving low-power electronics. While conventional RF energy harvesters are fabricated using conventional fabrication processes, this RF energy harvester is realized by inkjet-printing an antenna and the impedance matching circuit on a photo paper substrate. Only the top layers of such substrates are coated with a polymer, so that they readily absorb the water-based conductive ink. A coplanar waveguide design is presented to fulfill these requirements.

Key words: RF energy harvester, inkjet-printing, coplanar waveguide design

Introduction

Energy harvesting technologies based on thermoelectricity, piezoelectricity or solar cells are well known [1]. While the costs of the necessary components are quite high, harvesting energy from ambient RF sources is an alternative solution. Although the input power is below $1\,\mu W\,cm^{-2}$ it can be used to power low-power devices [2]. Furthermore ambient RF radiation has increased in several frequency bands over the last years, hence its getting easier to harvest energy [3] from ambient. Harvesting energy from RF sources in principle only requires an antenna to perform the transduction of electromagnetic waves into electrical signals, an impedance matching circuit for a maximum power transfer and a rectifier to convert the AC signal from an antenna into a DC signal [4]. With the exception of the rectifier these components can be easily fabricated using inkjet printing technology. Microwave structures at frequencies below 3 GHz have already been inkjet-printed by using a commercially available e.g. Epson inkjet printer [5].

This paper focuses on the fabrication of inkjet-printed multiband RF energy harvesters for two significant frequency bands, based on a coplanar antenna with matching circuit. Finally the results are compared with simulations to show the validity of inkjet-printed structures for RF applications.

Inkjet printing of conductive traces

The electrically conductive traces in this paper were inkjet-printed by using the drop-on-demand (DOD) technology. The most commonly used DOD technologies are bubble-jet or piezoelectric-jet based. A six-colour Epson Stylus Photo 1500W low-cost printer with a Micro Piezo print head is used by replacing a genuine cartridge with an empty refill one. Finally it was filled with a silver nanoparticle-based dispersion from Mitsubishi (NBSIJ-MU01). The viscosity (2.9 mPa s) and the surface tension ($32\,mN\,m^{-1}$) of this ink is comparable to the geninue ink.

By using the software CADlink FilmMaker the droplet volume (3 pl) and the ink density (30%) can be adjusted to achieve an electrical conductivity of $\sigma_{NAg} = 6 \times 10^6\,S\,m^{-1}$ immediately after printing onto photo paper substrates like HP, Epson or Canon [6]. With an additional thermal treatment process an electric conductivity of $\sigma_{NAg,sintered} = 14 \times 10^6\,S\,m^{-1}$ can be achieved. The printed layer thickness is approximately 800 nm. This is 23% of the conductivity of bulk silver ($\sigma_{NAg,bulk} = 61 \times 10^6\,S\,m^{-1}$). This heating process on the one hand removes organic compounds by vaporization and on the other hand induces a coalescence process of the nanoparticles. The conductivity is then sufficient good for printing antenna structures and transmission lines onto paper substrates.

RF ambient survey

For RF energy harvesters it is important to design the resonance frequency of the antenna according to the energy source. In this paper the sources with a maximum peak power in the surrounding area are used. Therefore, the ambient RF power was measured and logged for a day with an Aaronia HyperLOG 60100 broadband antenna ($\approx$ 70 cm^2). The peak power and the mean power were calculated and are shown in Fig. 1. Peaks can be typically found in the 2.4 GHz WiFi, GSM-900 and GSM-1800 frequency ranges.

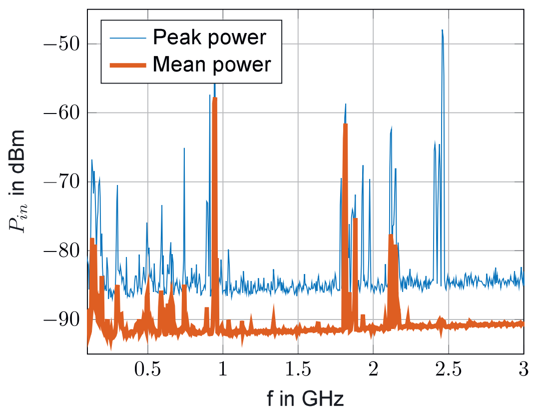

Fig. 1. Received RF peak and mean power in the considered environment for a reception area of 68 cm^2.

The resonance frequencies finally used for the antenna designs are $f_{\text{res},1}$ = 1.815 GHz and $f_{\text{res},2}$ = 2.445 GHz.

Coplanar antenna design

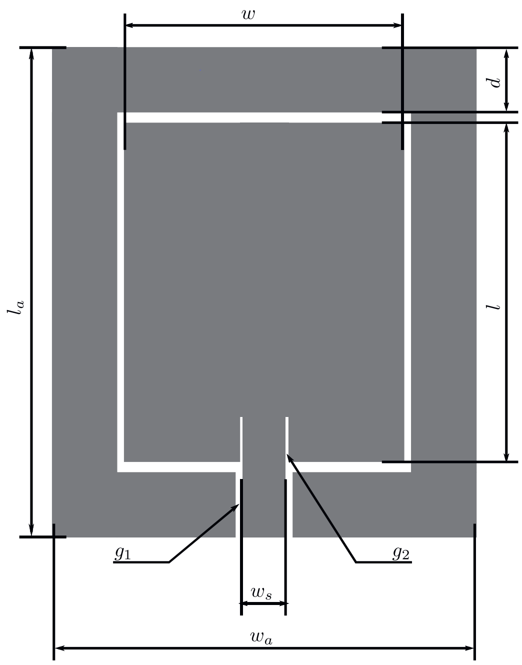

Fig. 2. Proposed coplanar antenna design.

On inkjet photo papers there is usually only one top layer coated with a polymer for absorbing the water-based conductive ink, so that microstrip antennas cannot be easily printed. To overcome this problem a coplanar antenna design is proposed and shown in Fig. 2.

The resonance frequency f_{res} of this antenna can be approximated by

$$f_{\text{res}} = \frac{c}{2w\sqrt{\frac{\epsilon_r+1}{2}}} \tag{1}$$

with the speed of light c and dielectric permittivity ϵ_r [7]. The calculated inner width w of the antenna was used as an initial parameter for an optimization process performed in Keysight ADS using the method of moments (MoM). The geometry was changed as long as no minimum of the scattering parameter S_{11} at the desired resonance frequencies were found.

As a substrate an HP Advanced Photo Paper was used. The material parameters were estimated using the proposed method in [5]. The dielectric constant was estimated to be $\epsilon_r = 4.5$ with a loss tangent tan $\delta = 0.14$. The thickness of the paper t = 0.25 mm. The results of optimization process for $f_{\text{res},1}$ and $f_{\text{res},2}$ are shown in Tab. 1.

Parameter	1.815 GHz	2.445 GHz
l	42.2	42.7
w	55	32.9
d	7.3	7.5
w_a	70.8	49.1
l_a	59.4	60.8
w_s	5.6	5.2
g_1	0.6	0.6
g_2	0.3	0.7

Tab. 1: Parameters for the proposed antenna design for two resonance frequencies.

Finally the antenna design was inkjet-printed two times on two different sheets of a HP Premium Photo Paper Advanced to verify repeatability and labelled as first and second print. The scattering parameters S_{11} were measured with Rhode & Schwarz ZND vector network analyzer and are shown in Fig. 3 and Fig. 4. The results are similar to the MoM simulation and shows the usability of inkjet-printed coplanar antenna structures.

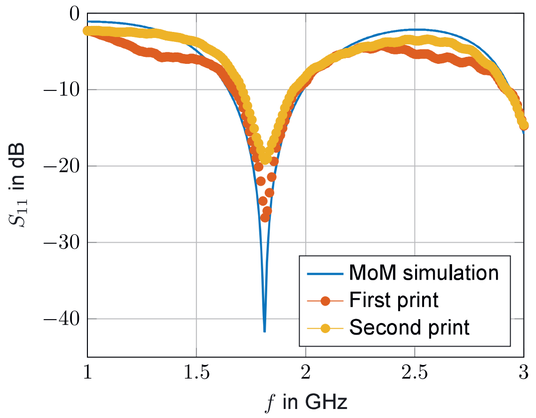

Fig. 3. Scattering parameter S_{11} of antenna designs at f_{res} = 1.815 GHz.

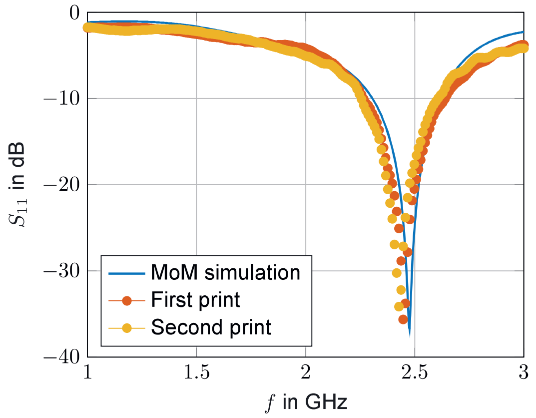

Fig. 4. Scattering parameter S_{11} of antenna designs at f_{res} = 2.445 GHz.

The gain of the antennas was calculated by using the Friis transmission equation, valid in the far-field

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{c}{f_{\text{res}} 4\pi R}\right)^2 \quad (2)$$

with the received power P_r, the transmitted power P_t, the antenna gain of the transmitting and receiving antenna G_t and G_r and the distance between the tansmitting and receiving antenna R. To calculate the antenna gain of the antennas, it can be assumed $G_r = G_t$, if the receiver and transmitter antennas are equal. For antenna 1 with $f_{\text{res},1}$ a gain of 2.2 dBi was measured, which is similar to the simulated gain 2.84 dBi. For antenna 2 with $f_{\text{res},1}$ a gain of 1.4 dBi was measured, which is similar to the simulated gain 1.62 dBi. The transmitting antenna was powered with P_t = 3 dBm, while the distance to the receiver was set to R = 2.14 m.

Rectifier design

The rectifier diode mainly influences the conversion efficiency of the overall energy harvester. Diodes with low turn-on voltage are necessary, hence highly efficient Schottky diodes have to be used. For the microwave range the type HSMS-286x from Avago with a low voltage sensitivity of 25 mV µW^{-1} are available for the frequency range of up to 5.8 GHz. Based on an HSMS-2862, which contains a pair of diodes connected in series a step-up circuit with a 3-stages Greinacher voltage doubler was designed (see Fig. 5).

The layout of the step-up circuit was finally inkjet-printed on a HP Photo Paper and is shown in Fig. (6). The Schottky diodes and the passive components were soldered at a temperature of 200 °C by using a combination of two different multicomponent solder alloys $Sn_{62}Pb_{36}Ag_2$ (melting temperature above 180 °C) and $Bi_{57}Sn_{42}Ag_1$. The first one contains a flux core and shows a better wettability on the components' pins, while the second one without flux core does not destroy so easily the thin printed layer, due to a lower melting temperature of 140 °C.

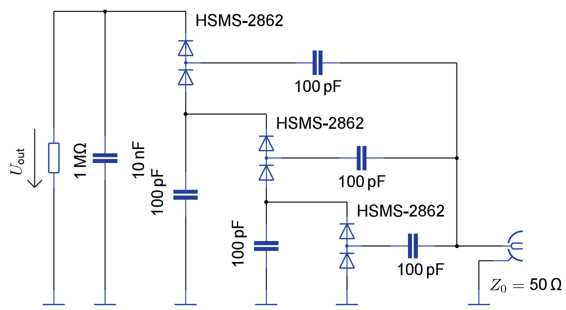

Fig. 5. Schematic of a three stage voltage doubler and a 1 MΩ load.

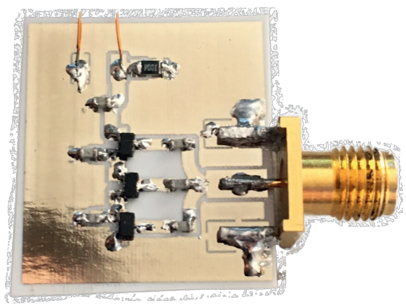

Fig. 6. Inkjet-printed voltage doubler with three stages and an SMA-connector for impedance measurement.

Furthermore a Smith chart diagram shows the normalized measured impedances for various input powers and is depicted in Fig. 7. The input impedance depends on the input power, due to the non-linear components in the circuit.

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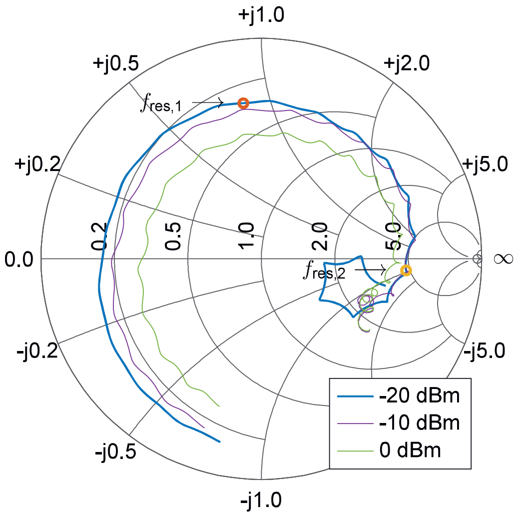

Fig. 7. Smith chart for different input powers.

For further optimizations the input impedance of the step-up circuit at a input power of -20 dBm was found to be $Z_L = (14.8 + j \cdot 42.3)\,\Omega$ for $f_{\text{res},1} = 1.815$ GHz and $Z_L = (235.0 - j \cdot 43.4)\,\Omega$ for $f_{\text{res},2} = 2.445$ GHz. The imaginary part is mainly generated by the junction capacitance of the diode.

Rectifier impedance matching

An impedance matching network is necessary to transfer the maximum power of the antenna signal to the step-up circuit. To cancel out the imaginary part of Z_L two transmission lines with different electrical lengths and line impedances are used as shown in Fig. 8 and 9.

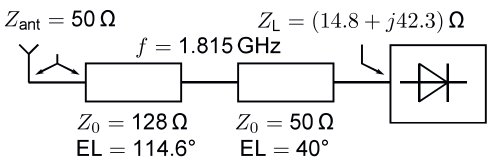

Fig. 8. Impedance matching with transmission line at 1.815 GHz.

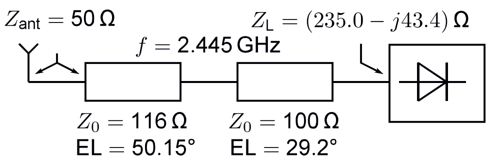

Fig. 9. Impedance matching with transmission line at 2.445 GHz.

By using coplanar transmission lines as shown in Fig. 10 an impedance circuit can be finally achieved.

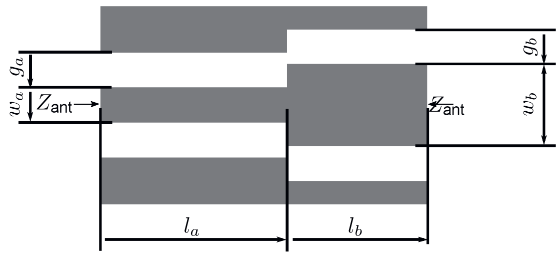

Fig. 10. Coplanar transmission line for impedance matching.

The parameters for the coplanar design were calculated by using ADS Linecalc. The final optimization results are shown in Tab. 2.

Parameter	1.815 GHz	2.445 GHz
w_a	3	2.5
w_b	4.9	2.9
l_a	46.3	15.4
l_b	14.4	8.7
g_a	0.2	1.6
g_b	1.9	1.6

Tab. 2: Parameters of an optimized coplanar impedance matching circuit.

The matching circuit was finally connected to the step-up circuit to validate the matching. In Fig. 11 the scattering parameter S_{11} show good matching at 2.445 GHz and the similarity between the MoM simulations and measurement. Furthermore it shows, that the results produced by Linecalc are already sufficient for a good matching.

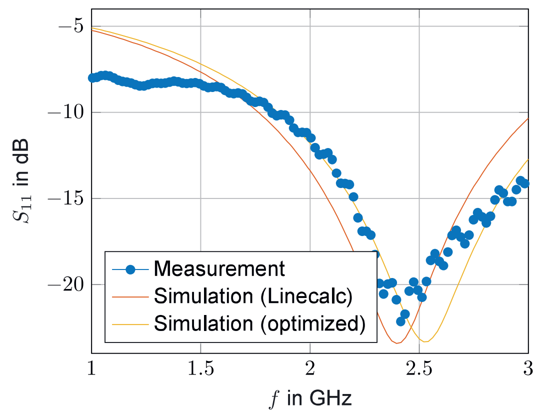

Fig. 11. Scattering parameter S_{11} of the step-up circuit.

The step-up circuit was powered with an input power of -10 dBm to measure its output voltage. The first step-up circuit achieves a voltage of 150 mV at a load of 220 kΩ at $f_{\text{res},1}$. The step-up circuit for $f_{\text{res},2}$ only achieves a voltage of 95 mV at a load of 220 kΩ.

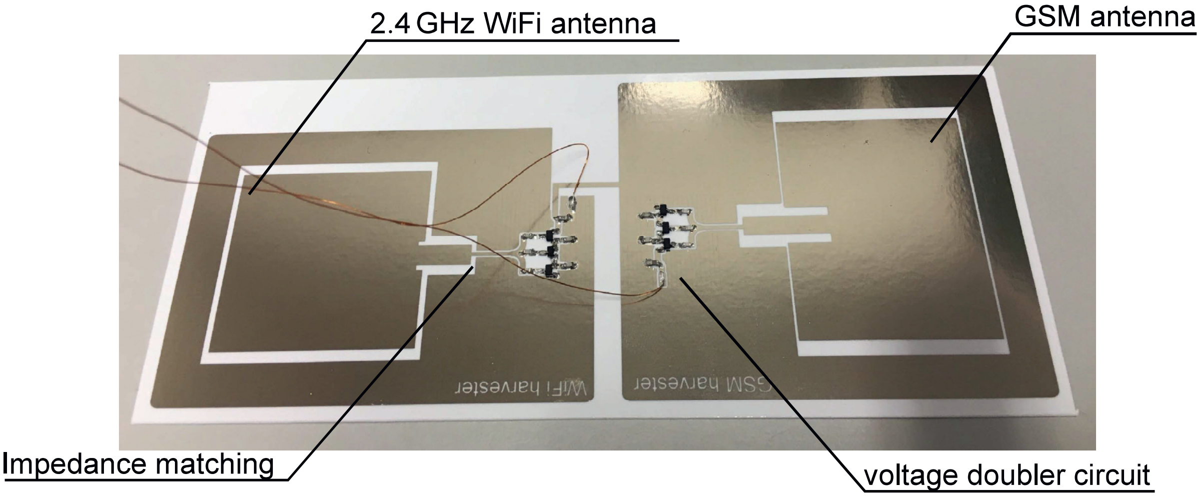

Fig. 12. Inkjet-printed prototype with two separate RF energy harvesters for 1.815 GHz *and* 2.445 GHz *bands.*

Results

A multiband energy harvester based on the GSM-1800 and the 2.4 GHz WiFi frequency bands was developed and a layout is shown in Fig. 12. A cellular phone in the near field of the inkjet-printed prototype and an active WiFi or voice connection is able to generate a voltage of up to 3 V. This voltage is sufficient to directly drive a low-power microcontroller.

Conclusion

In this paper an inkjet-printed energy harvester with two antennas, impedance matching and step-up circuits was presented. The coplanar waveguide antenna structures were simulated in Keysight ADS and optimized for a resonance frequency of 1.815 GHz and 2.445 GHz. The input power of the WiFi and GSM signals are quite low, so a highly efficient step-up circuit was required. A full-wave three-stage Greinacher rectifier was used. The simulation and measurement results finally shows the usability of inkjet-printed RF structures.

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