Broadband High-Efficiency Microwave Rectifier with Nonuniform Transmission-Line Input Matching for Harmonic Backscattering Applications

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***Abstract*— The second harmonic produced by the nonlinearity of a diode rectifier can be utilised for backscattering communication. A rectifier for this purpose should not suppress the second harmonic, but its emergence should be embraced in the design. With a traditional transmission-line matching network, composed of serial lines and stubs, it becomes difficult to ensure a high power level of the second harmonic. We propose the use of a nonuniform transmission line (NUTL) to resolve this issue. The NUTL allows nearly uncompromised travel of the second harmonic power. Furthermore, it can enhance the bandwidth of a rectifier. A diode rectifier in voltage doubler configuration with a NUTL matching network, enabling the emission of the second harmonic and efficient operation over a broad frequency range is demonstrated. It has a maximum measured power conversion efficiency (PCE) of 76.5 % at 2.5 GHz and 23.9 dBm input power while backscattering 2.8 dBm at the second harmonic and is able to maintain a PCE higher than 60 % from 2 GHz to 2.75 GHz and above 70 % from 2.25 GHz to 2.65 GHz.**

***Keywords*— backscattering, broadband, rectifier, voltage doubler, wireless power transfer, nonuniform transmission line (NUTL)**

I. INTRODUCTION

When using a nonlinear device to rectify microwave to dc power, harmonic frequencies will be generated. Traditionally, these harmonics are controlled or suppressed on purpose to boost the power conversion efficiency (PCE) of a rectifier [1].

In harmonic backscattering the second harmonic is used to establish a backward communication channel. In [2], [3] the harmonic power generated by the rectifier is directly employed for this purpose. To modulate the throughput of the harmonic power, a variable bandpass filter and a controllable second harmonic termination (CSHT), which is incorporated in the input matching network, respectively, are used. Using the harmonic power directly generated by the rectifier offers a power efficient implementation, as no additional signal source is needed. However, these implementations usually have a narrow bandwidth and comparatively low PCE.

The input matching network is a major factor when designing a high-frequency rectifier. It influences bandwidth, PCE as well as the amount of backscattered harmonic power. A traditional transmission-line (TL) matching network consists of at least one serial line and one stub, as shown in Fig. 1a. Such an approach brings certain difficulties when using the rectifier for harmonic backscattering, as the second harmonic might effectively be suppressed, when the electrical length of the TLs or stubs is close to $\lambda/4$ or $\lambda/2$ at the second harmonic. Furthermore, it optimises the PCE at a single frequency, resulting in a narrowband design.

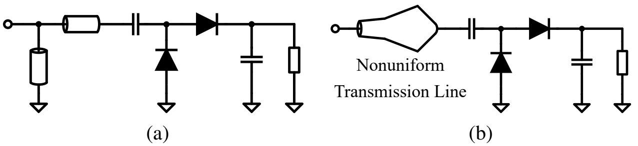

Fig. 1. Rectifier input matching using (a) traditional and (b) nonuniform transmission line.

To increase the bandwidth of a rectifier, various input matching networks have been reported such as a multistage inductor-capacitor (MSLC) network [4], an exponential taper transmission line (ETTL) [5], and a nonuniform transmission line (NUTL) [6], [7]. But the second harmonic behaviour has not been taken into account in these designs.

Designing a wideband backscattering rectifier is challenging because it has to simultaneously obtain a high PCE and a reasonable power level at the backscattered second harmonic over a broad frequency range. Therefore, we propose the use of a nonuniform transmission line (NUTL) as the input matching network of a wideband rectifier designed for backscattering applications in particular, as shown in Fig. 1b. Using a NUTL can ensure nearly uncompromised travel of the second harmonic from the rectifier to the input node while enabling a high PCE over a broad frequency range. This combination enables a power efficient wireless power reception and information backscattering in wireless power transfer systems at high frequencies. To demonstrate the performance, a voltage doubler rectifier with a NUTL input matching network is designed, implemented, and measured.

II. CIRCUIT DESIGN AND NUTL SYNTHESIS

The behaviour of a NUTL has been studied in [8]. To design a NUTL for this rectifier, it is discretized as shown in Fig. 2. The length of the NUTL, L, is divided into sections of length, dz, each of which has a constant width. Assuming the difference in width between each neighbouring section is small enough to ensure a smooth impedance change, the whole NUTL can be seen as a cascade of very short microstrip transmission lines. For each width, the characteristic impedance and the effective dielectric constant

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doi: 10.1109/IMS40175.2024.10600230.

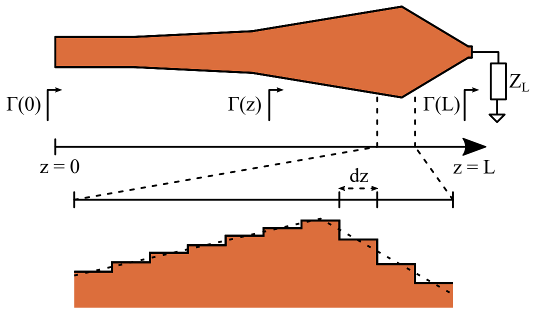
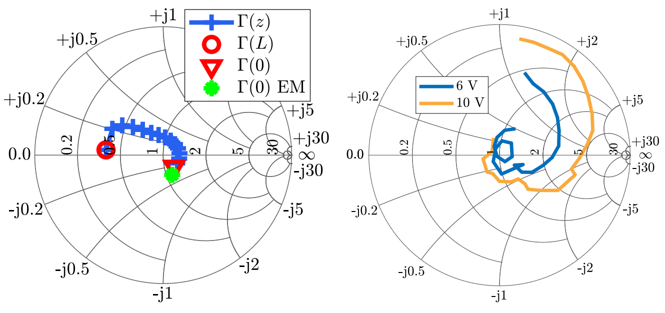


Fig. 2. Discretisation of the NUTL width for approximative reflection coefficient calculation.

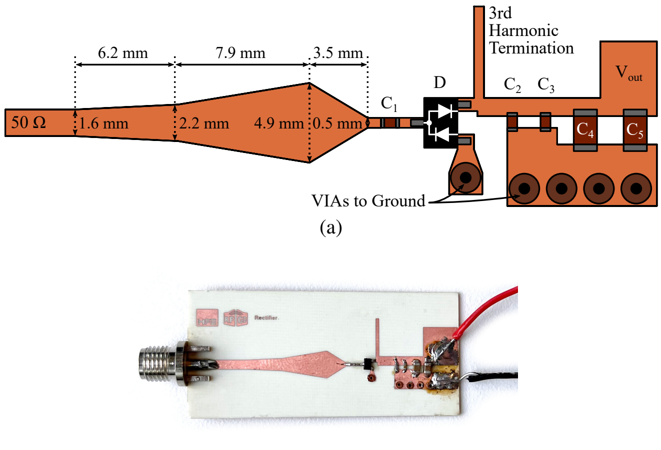


(a) (b)

Fig. 3. (a) Reflection coefficient over the length of the NUTL and EM simulated input reflection coefficient and (b) EM-simulated input reflection coefficient of the circuit at 24 dBm input power over frequency from 1.8 GHz to 3 GHz.

can be determined. Using these, the change of the reflection coefficient over the nonuniform transmission line can be analysed.

Starting at the load side, $z = L$, the impedance equals the load impedance, Z_L, and the reflection coefficient, $\Gamma(L)$, can be determined with regard to the characteristic impedance of the section at $z = L$. Moving towards the input side of the NUTL, *i.e.* $z = 0$, at each section change, the reflection coefficient is renormalised to the characteristic impedance of the next section and turned in angle according to the phase change caused by the section. In Fig. 3a this impedance-change path along the NUTL is shown. The impedance of the voltage doubler including the input capacitor is used as the load impedance, Z_L, *i.e.* $\Gamma(L)$, of the NUTL. From this starting point which is $\Gamma(L)$, the movement of the reflection coefficient with regard to each of the sections is shown as $\Gamma(z)$. The theoretically calculated input reflection coefficient, $\Gamma(0)$, is close to the one obtained from the full EM-simulation. It indicates that by aid of the calculation a suitable configuration, *i.e.* initial dimensions, of the NUTL can be approximately found and afterwards it can be further optimised in the EM-simulation environment. For example, in this design Matlab and Keysight ADS Momentum are employed for the theoretical calculation and EM-simulation, respectively. It is crucial to find sensible initial dimensions of the NUTL. As the NUTL has a very high degree of freedom, many dimensions need to be tested to find one with good performance. Evaluating this using EM-simulations would consume a significant amount of computational effort.



(a)

(b)

Fig. 4. Rectifier (a) schematic with dimensions and (b) photograph of the PCB. The PCB measures 40 mm x 20 mm

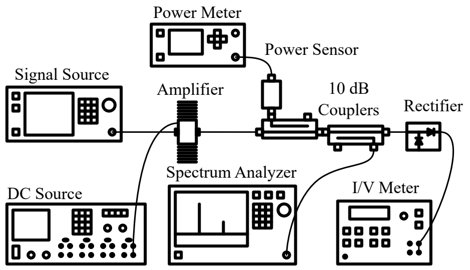


Fig. 5. Measurement setup.

The design resulting from this process is shown in Fig. 4. Three tapered transmission lines form the NUTL and Infineons BAT68 diodes in antiparallel connection are used. The circuit is implemented on a Rogers 4350b substrate. The simulated input reflection coefficient at 24 dBm input power over frequency is shown in Fig. 3b. At 6 V dc output voltage, the circuit is matched better than 10 dB from 2.25 GHz to 3 GHz. At the increased output voltage, the matching performance worsens, especially at the lower frequency range.

III. MEASUREMENTS

The measurement setup is shown in Fig. 5. The input signal is amplified and fed through two 10 dB directional couplers connected back-to-back. A power meter with a power sensor is connected to the coupled port of the first directional coupler to measure the incoming power at the fundamental, P_{in}. The coupled port of the second one is connected to a spectrum analyzer to measure the backscattered power at the second harmonic, P_{harm}. The rectifier dc output voltage is set by an I/V-meter and the output current is measured to get the output power, P_{DC}. The PCE is calculated as $PCE(\%) = 100 \cdot P_{DC}/P_{in}$.

Fig. 6 shows the measured and simulated PCE and the power of the backscattered signal at the second harmonic with a fundamental signal at 2.5 GHz for various output voltages.

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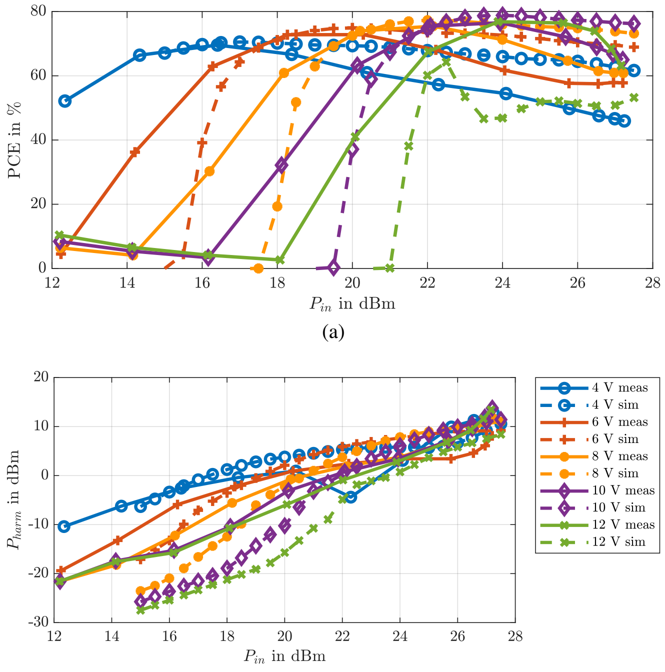

(a)

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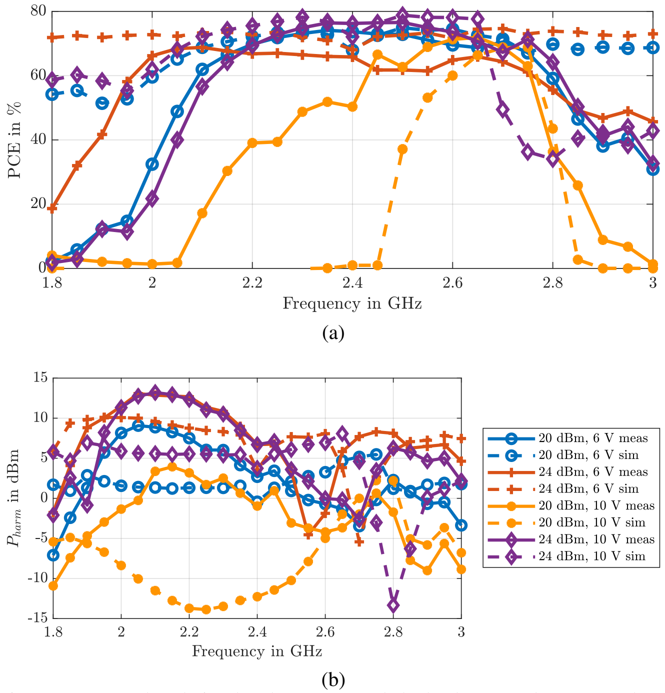
Fig. 6. Measured and simulated (a) PCE at a fundamental frequency of 2.5 GHz and (b) backscattered power at the second harmonic over input power.



(a)

(b)

Fig. 7. Measured and simulated (a) PCE and (b) backscattered power at the second harmonic over frequency at various output voltage and input power combinations.

Table 1. Comparison with state-of-the-art work.

Metric	This Work	[2]	[3]	[4]	[5]	[6]	[7]
Max. PCE							
PCE (%)	**76.5**	51†	59†	71.7	68.8	69†	75.8
f_{in} (GHz)	**2.5**	2.4†	2.4†	2.75	0.915	0.5†	2.5
P_{in} (dBm)	**23.9**	0	0	24	21	10	14
Band PCE							
> X (%)	**60**	50	50	50	50	60	70
P_{in} (dBm)	**24**	0	0	20	17	10	10
f_{min} (GHz)	**2**	2.3†	2.3†	0.39	0.06	0.47	2
f_{max} (GHz)	**2.75**	2.5†	2.5†	2.9	3.95	0.86	3.05
Harmonic							
P_{2nd} (dBm)	**7.1**	-28†	-14†	-	-	-	-
P_{in} (dBm)	**25.7**	0	0	-	-	-	-
f_{in} (GHz)	**2.5**	2.4	2.4	-	-	-	-
Matching	**NUTL**	STL	CSHT	MSTL	ETTL	NUTL	NUTL
Diode	**BAT68**	HSMS 285B	HSMS 285B	1PS70 SB82	HSMS 286C	SMS 7630	HSMS 286
Size							
X (mm)	**40**	40†	20†	9	2.8‡	190†	36
Y (mm)	**20**	30†	25†	11	50.5‡	30†	35

† From Figure; ‡ Active Only; STL: Serial Transmission Lines

The simulation results are obtained using an EM-model and the Spice model of the diodes provided by the manufacturer. The simulated and measured PCE in general are close to one another. A discrepancy at 12 V dc output voltage is observed. It may be due to the breakdown voltage of the diode not being accurately modelled. A high PCE is maintained while backscattering a considerable amount of power at the second harmonic, *e.g.* the backscattered power is measured to be 7.1 dBm at 25.7 dBm input power and 12 V output voltage, while the PCE is 76.4 %. The second harmonic power is large enough to be detected and utilised for backscattering communication, but it takes up approximately 1.4 % of the input power only, allowing for a high PCE still. At 23.9 dBm input power it has a maximum measured PCE of 76.5 % at 2.5 GHz while backscattering 2.8 dBm at the second harmonic. The measured backscattering powers are sufficient for information decoding.

The measured and simulated PCE and the backscattered harmonic power over frequency are given in Fig. 7. PCE is above 60 % from 2 GHz to 2.75 GHz and above 70 % from 2.25 GHz to 2.65 GHz. The maximum PCEs of the circuit are well approximated by the simulation. At the high output voltage and low input power state, *i.e.* 10 V, 20 dBm, the simulation underestimates the bandwidth and the reflected harmonic power below 2.6 GHz. These results suggest a more accurate Spice model of the diode is needed for future optimisation as a high-frequency rectifier.

The performance of the presented rectifier is compared to state-of-the-art in Table 1. It has the highest PCE and the widest bandwidth compared to the ones used for harmonic backscattering, *i.e.* [2], [3], at a higher input power, at which, to the authors' best knowledge, this paper is the first to present such a design. The dimensions are comparable to the other implementations using matching networks. Despite the high backscattering power offered by the rectifier, the efficiency is competitive with literature. Note that in this work the high input power is deliberately designed to obtain sufficient dc output power for the targeted application. The input power level can be scaled down using different diodes.

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IV. CONCLUSION AND OUTLOOK

We presented a voltage-doubler rectifier using a NUTL as an input matching network for backscattering applications. The input matching using a NUTL can be used not only to enhance the bandwidth but also to allow the travel of the second harmonic frequency to implement harmonic backscatter communication. The NUTL enables the performance as well as compact size presented here. A fast and reliable approach to synthesise the NUTL was proposed and confirmed. The second harmonic created by the rectifier was demonstrated to have a high power for further use for a backscatter communication channel, while the PCE remains high over a broad frequency range.

ACKNOWLEDGMENT

This work is part of the the NeuroSys Project. NeuroSys as part of the initiative "Clusters4Future" is funded by the Federal Ministry of Education and Research BMBF (03ZU1106CA).

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