Compact Broadband Voltage Doubler Rectifier with Nonuniform Transmission Line Based Input Matching

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***Abstract*— We present a voltage doubler rectifier whose input matching is realised by a nonuniform transmission line, which allows for a broadband behaviour in a compact size. A design methodology for the rectifier including the nonuniform transmission line is proposed. To demonstrate the feasibility and application of the design methodology, a broad operation frequency band is targeted. The design resulting from the proposed method using a BAT15-04W diode is implemented and measured. Measurements confirm the broadband behaviour, achieving above 50 % power conversion efficiency from 0.5 GHz to 5 GHz at 18 dBm input power. The size of the PCB is 1.8 cm times 1.6 cm on a Rogers RO4350b substrate. It presents the highest maximum frequency of 5 GHz and the highest absolute bandwidth of 4.5 GHz, which is enabled by the use of the nonuniform transmission line.**

***Keywords*— broadband, compact, nonuniform transmission lines, rectifiers.**

I. Introduction

Rectifiers are crucial elements in wireless power transfer systems, as they convert the power of an incoming RF signal into a universally usable dc voltage [1]. The Greinacher circuit, as shown in Fig. 1a, outputs up to double the peak voltage of the input RF signal, which makes it a popular choice for energy harvesting applications. At the negative half cycle of the sine wave of the input voltage, the parallel diode, D_P, conducts, charging the capacitor, C_D, to the peak voltage of the sine wave. In the positive half cycle, the serial diode, D_S, conducts, charging C_L to the voltage of the serial connection of the input voltage and the voltage of C_D, *i.e.*, two times the peak voltage of the sine wave.

The input impedance of the circuit needs to be matched to the source impedance for a high conversion efficiency. This is commonly done using transmission-line networks [2] or discrete elements [3]. Nonuniform transmission lines (NUTLs) have a varying width along the length of the line, and can thereby be designed to purposefully transform a given set of impedances [4]. It has been demonstrated that NUTLs can be used to realise the matching of broadband rectifiers [5], [6], and to enable uncompromised travel of the generated harmonics for harmonic backscattering systems [7].

In this paper, a design methodology for a rectifier using NUTLs is proposed. To prove the methodology and to take advantage of the NUTL, a broadband operation frequency is targeted, while preserving a compact size without using more than the necessary discrete components. The circuit configuration including the NUTL and three uniform transmission lines, TL_P, TL_S, and TL_C, is given in Fig. 1b. The stub, TL_C, presents a defined capacitance at the load side of the diodes at high frequencies, at which the resonance frequency of the capacitors is surpassed. The NUTL and the two transmission lines, TL_P and TL_S, enable the degrees of freedom needed to optimise the performance of the rectifier over a broad operating frequency range. Since the theoretical analysis of an NUTL is complex, and there might be more than one NUTL that offers a sensible solution, it poses a certain challenge in the design process.

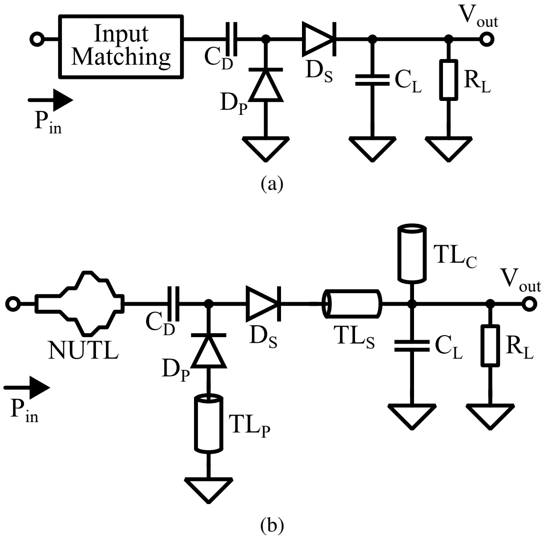


Fig. 1. Greinacher voltage doubler (a) general configuration, and (b) configuration used for optimisation.

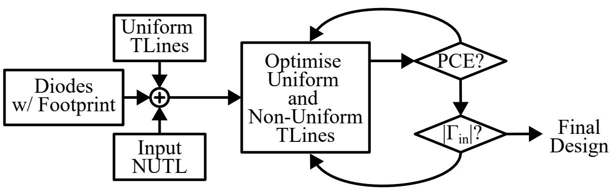


Fig. 2. Proposed design methodology for a rectifier utilising an NUTL.

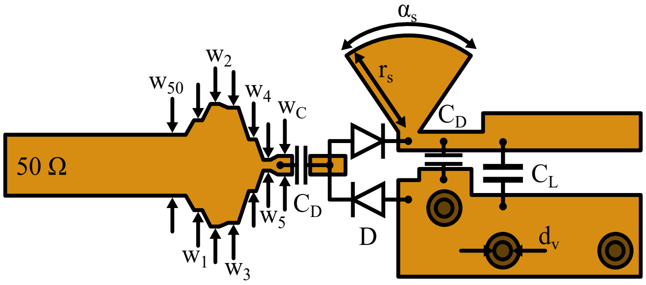


Fig. 3. Layout of the designed rectifier.

Table 1. Design parameters.

w_{50} (mm)	w_1 (mm)	w_2 (mm)	w_3 (mm)	w_4 (mm)	w_5 (mm)
1.64	2.42	3.3	3.1	1.39	0.29

w_C (mm)	r_s (mm)	α_1 (°)	d_v (mm)	C_D (pF)	C_L (μF)
0.5	2.5	70	0.9	10	4.7

II. Design Methodology

The input NUTL is realised as a cascade of six tapered transitions combining five uniform transmission lines. The uniform transmission lines each have a variable width, w_1-w_5, and both the uniform lines and the tapered lines all have the same very short length, dx. The widths, w_1-w_5, and dx are used as parameters for the optimisation process. This way, the NUTL can be simulated on a schematic level first for a speedy initial design despite the multitude of design parameters, and afterwords it can be automatically transferred to the EM-simulation environment for fine-tuning.

The design methodology is illustrated in Fig. 2. It is realised using Keysight ADS. In a first step, all components are added to the circuit. The diodes include their EM-simulated footprint. The design is then optimised for power conversion efficiency (PCE) and proper input reflection coefficient, $|\Gamma_{in}|$. All optimisation parameters, w_1-w_5, dx, and the lengths of the uniform transmission lines, TL_P, TL_S, and TL_C, are kept as optimisation variables. When the desired PCE is reached, the input matching is checked, and further optimisation regarding the input matching might be needed. The design is alternatingly optimised for PCE and input matching until both reach the desired goals, simultaneously.

III. Prototype and Measurement Results

A prototype is designed using the proposed methodology with the goal of achieving above 50 % PCE from 0.5 GHz to as high a frequency as possible. The final design is given in Fig. 3 and its design parameters are listed in Table 1. The diodes, model BAT15-04W from Infineon, are within a single package, and have a rated breakdown voltage of 4 V. TL_C is realised as radial stub for broadband performance. During the design process it became obvious that for this particular diode model, the optimal lengths of the transmission lines, TL_P and TL_S, is as short as possible, wherefore the capacitance,

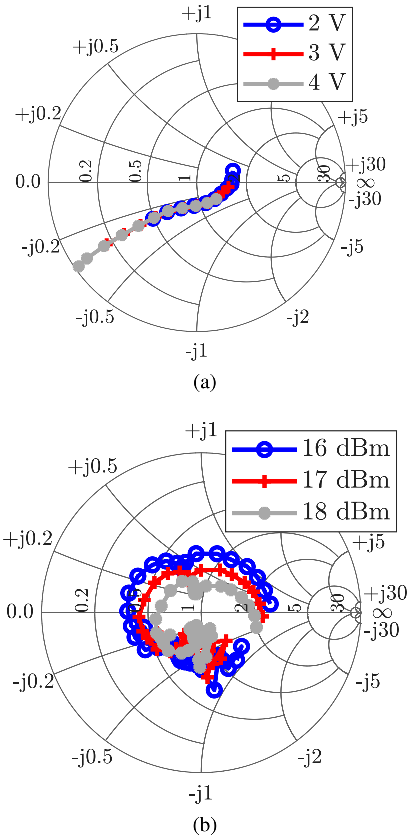


Fig. 4. Simulated input reflection coefficient (a) over input power from 12 dBm to 22 dBm at 2.5 GHz and (b) over frequency from 0.5 GHz to 5 GHz at 3 V output voltage.

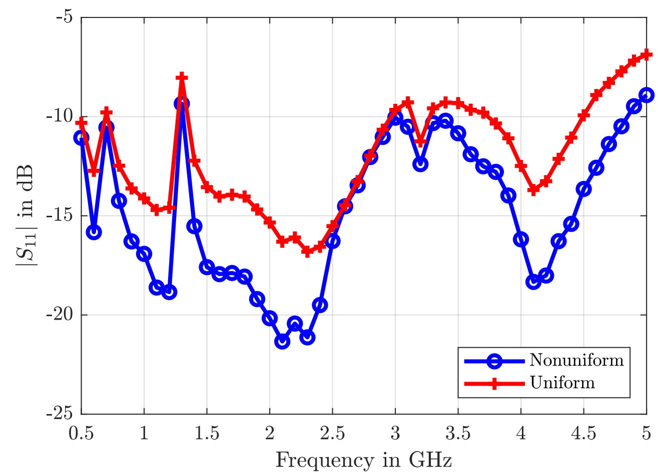


Fig. 5. Simulated input matching compared to a uniform transmission line input at 18 dBm input power and 3 V output voltage.

C_D, is placed in close proximity to the diodes. The simulated input reflection coefficient over input power and frequency, using the diode spice model provided by the manufacturer, is given in Fig. 4. At the highest output voltage, the input matching is worse at the lowest input power levels. Input matching over frequency is improving towards higher input powers.The simulated matching performance of the designed

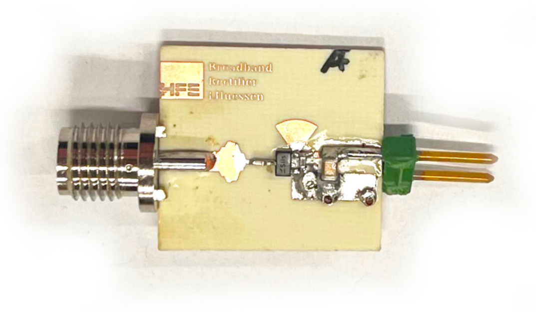


Fig. 6. Photograph of the manufactured rectifier PCB measuring 1.8 cm × 1.6 cm.

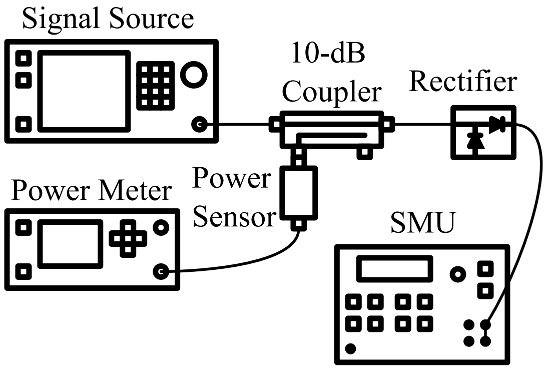
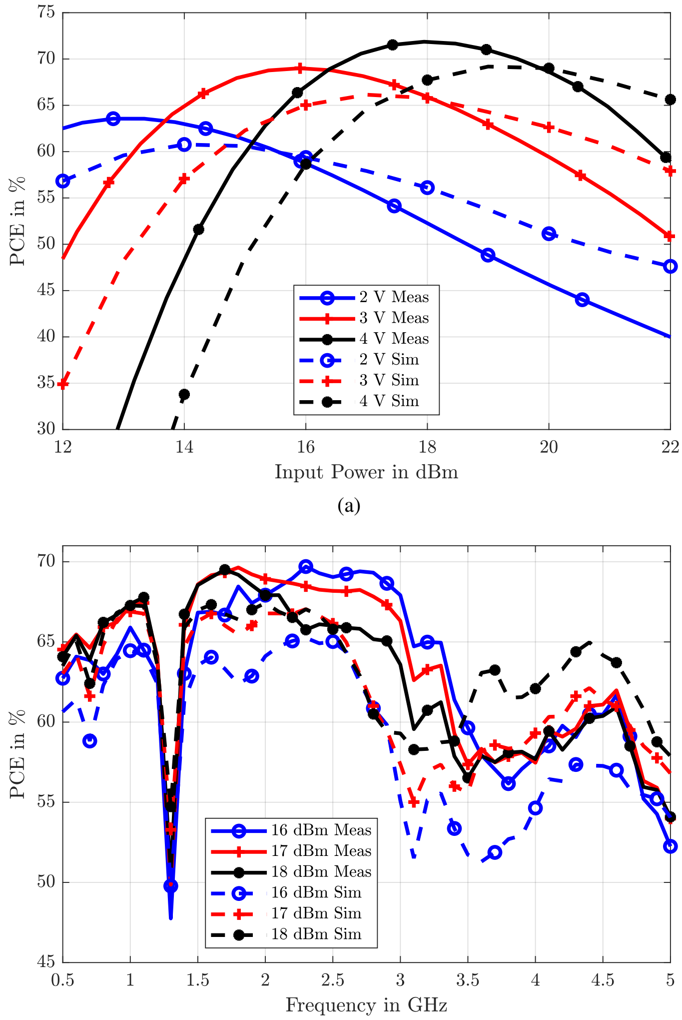


Fig. 7. Rectifier measurement setup.

rectifier utilising the NUTL is compared to a design utilising a uniform $50\,\Omega$ input line in Fig. 5. The NUTL improves the matching performance over the full bandwidth, and makes a significant difference towards the higher frequencies.

The rectifier is manufactured on a 0.762 mm-thick Rogers 4350b substrate in house. The PCB, measuring $18\,\text{mm} \times 16\,\text{mm}$ is shown in Fig. 6. Its size can be further reduced, as the active copper area measures only $17.7\,\text{mm} \times 6.6\,\text{mm}$. The performance is measured using the setup outlined in Fig. 7. The input signal is generated by a Rohde & Schwarz SMBV100A signal generator. Its power, P_{in}, is measured by a HP 8485A power sensor via a Krytar 10-dB directional coupler and displayed by an Agilent E4418B power meter. A Yokogawa GS610 is used as source measurement unit (SMU) posing the load of the rectifier. The output voltage, V_{out}, is fixed by the SMU and the output current, I_{out}, is measured. This resembles the behaviour of a power management IC with maximum power point tracking capability, which will be the rectifier load in later application. The S-parameters of the directional coupler are regarded in the measurement postprocessing. The PCE in percentage is calculated as $100\% \cdot (I_{out}V_{out})\,/P_{in}$.

In Fig. 8a the measured and simulated PCE is given over input power at various V_{out} at a frequency of 2.5 GHz. From 12 dBm to 22 dBm the PCE of the rectifier can be kept above $60\,\%$ by adjusting V_{out}. The simulation shows the highest PCE at slightly higher input power than the measurements, indicating an overestimation of the threshold voltage of the diode, but otherwise follows the trajectory of the measurement well. The maximum measured PCE is $71.86\,\%$ at 18 dBm input



(a)

(b)

Fig. 8. PCE over (a) input power at 2.5 GHz and (b) frequency at 3 V output voltage.

power and 4 V output voltage.

The measured and simulated PCE over frequency are shown in Fig. 8b. At 18 dBm input power the PCE is above $50\,\%$ over the full frequency range from 0.5 GHz to 5 GHz. At 17 dBm the PCE is above $60\,\%$ from 1.4 GHz to 3.1 GHz. The figures display the measured maximum PCE operating points, wherefore the simulated PCE values are mostly slightly lower than the measured ones. In simulation, these PCE values are surpassed at higher power operating points. The dip in PCE at 1.3 GHz is observed in both simulation and measurement, indicating an undesired resonance frequency here on the one hand, but also hinting toward proper simulation of the passive structures.

The performance of the presented rectifier is compared to designs from literature in Table 2. It presents the highest maximum frequency of 5 GHz and the highest absolute bandwidth of 4.5 GHz, which is enabled by the use of the NUTL. Furthermore it has a compact size, which could be further reduced as the active copper of the PCB only measures $17.7\,\text{mm} \times 6.6\,\text{mm}$.

Table 2. Comparison of voltage doubler rectifiers.

Ref.	PCE (%)	@P_{in} (dBm)	BW (GHz)	FBW (%)	Max PCE (%)	@$P_{in,max}$ (dBm)	Diode	Size (mm^2)
[8]	>70	17.2	2.08-2.58	21.5	80.8	17.2	HSMS286F	126 x 68
[9]	>50	10-27	0.06-3.32	192.9	77.3	23	HSMS-2862-TR1	20 x 7.4
[2]	>50	15	0.2-3.2	176.5	78.2	18	BAT15-03W	38 x 15
[10]	>50	18	0.1-4.3	190.9	76.36	18	BAT15-04W	15 x 8
[11]	>60	18	0.3-2.9	162.5	79.8	19	BAT15-04W	19 x 18
This Work	**>50**	**18**	**0.5-5**	**163.6**	**71.86**	**18**	**BAT15-04W**	**18 x 16**
	>60	**17**	**1.4-3.1**	**75.56**				

IV. Conclusion

The designed compact rectifier achieves above $50\,\%$ PCE over a frequency range from $0.5\,\mathrm{GHz}$ to $5\,\mathrm{GHz}$ and above $60\,\%$ PCE from $1.4\,\mathrm{GHz}$ to $3.1\,\mathrm{GHz}$. The use of the NUTL as input matching enables the bandwidth extension up to $5\,\mathrm{GHz}$, while retaining a compact size with only $17.7\,\mathrm{mm} \times 6.6\,\mathrm{mm}$ active copper without the use of more than the core components needed in the Greinacher voltage doubler configuration. It can be used for wireless power transfer applications in the future.

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