

High-Efficient Inverse Class-F Power Amplifier Utilising Nonuniform Transmission Lines for Wireless Power Transfer

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Abstract—An RF power amplifier (PA) for wireless power transfer (WPT) differs from one used for communication. Particularly, a PA for WPT prioritizes efficiency over linearity. A switching-mode PA (SMPA) is thus ideal for this purpose. In this paper, we present a highly efficient inverse class-F SMPA utilizing nonuniform transmission lines (NUTLs). The load transformation network (LTN) ensures that at the fundamental frequency the optimum impedance and at the harmonics the corresponding impedances are presented to the drain of the transistor for an inverse class-F SMPA operation. A discrete 6W GaN transistor is employed in a prototype, which demonstrates a power-added efficiency of 72.7 % and a gain of 13.4 dB at 2.42 GHz. The measured second and third harmonic suppression are -38.5 dBc and -41 dBc, respectively.

Keywords—Wireless power transfer (WPT), Inverse Class-F, Nonuniform Transmission Lines (NUTL), Power Amplifier, Switching Mode

I. INTRODUCTION

For a wireless power transfer (WPT) system, as shown in Fig. 1, a high-efficiency power transmitter (TX) [1], [2] is required. In such a TX for WPT, the most critical parameter is the efficiency instead of the linearity usually required in a typical communication TX. Furthermore, the power TX has to generate sufficient output power. This makes a switching-mode power amplifier (SMPA) a promising candidate.

Nonuniform transmission lines (NUTLs) have a varied width along the length of the line and the characteristic line impedance changes accordingly depending on the position on the line. This enables the targeted design of NUTLs to transform impedances [3]. NUTLs are predominantly utilised to enhance the bandwidth of RF circuits. For example, a rectifier [4], a linear hybrid power amplifier (PA) [5], and recently a broadband monolithically integrated linear PA [6] have been demonstrated.

A load transformation network (LTN) is used in a PA to transfer the output load impedance, *e.g.* 50Ω, to the optimum impedance required by the transistor. SMPAs, however, require the impedance to be controlled not only at the fundamental frequency but also the harmonics. An LTN for an inverse class-F SMPA is traditionally designed using transmission lines (TLs) and stubs as shown in Fig. 2a[7].

In this paper, we implement an SMPA using NUTLs for a WPT system. The main challenge in an SMPA compared

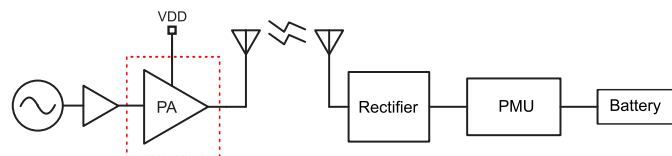


Fig. 1. Diagram of a typical wireless power transfer system.

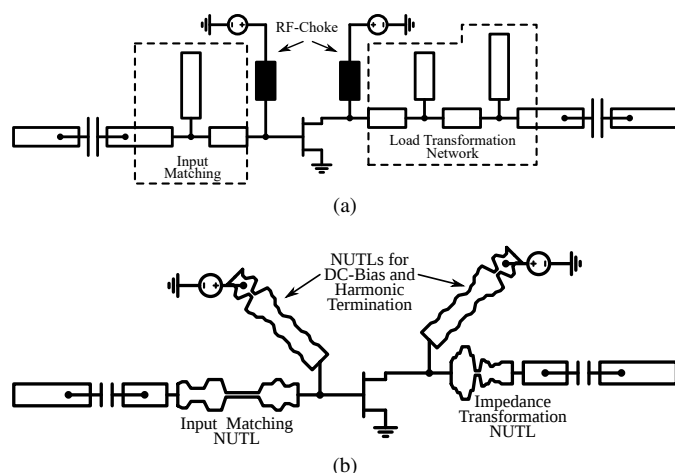


Fig. 2. (a) Traditional and (b) proposed NUTL-based inverse class-F PA design.

to a linear PA is that the impedances at the harmonics have to be controlled to obtain the correct operation. The goal is therefore to verify the feasibility of the impedance control for the fundamental frequency and the harmonics as well as suppressing the harmonics using only NUTLs. The proposed inverse class-F SMPA using NUTLs is shown in Fig. 2b.

II. SMPA DESIGN

The SMPA consists of an input matching network (IMN), an LTN and a transistor as a switch together with the gate and the drain biasing networks (BNs), as shown in shown in Fig. 2b. As depicted, IMN, BNs, and the LTN are NUTLs. The design of the NUTL-based inverse class-F PA is carried out in Keysight Advanced Design Systems (ADS).

The NUTLs are implemented as cells containing eleven tapered transmission-line and ten transmission-line elements,

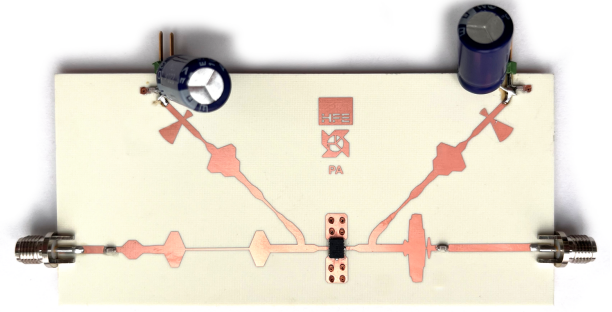
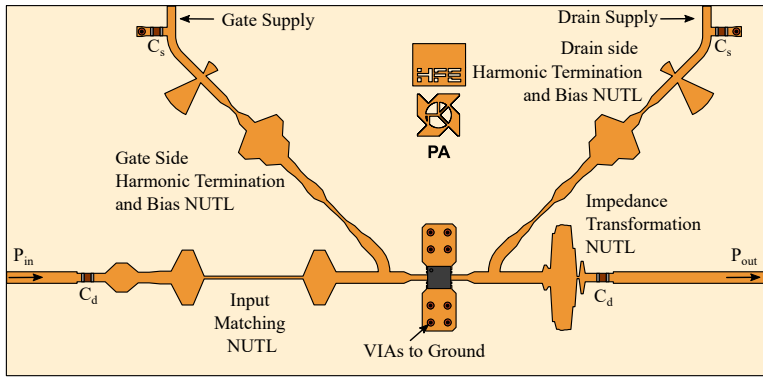


Fig. 3. (a) Layout and (b) Photograph of the NUTL based inverse Class-F PA.

alternately. The widths of the ten transmission-line elements are set by ten independent width parameters, and the tapers connected the neighbouring elements. The lengths are the same for all elements and set by a length parameter.

Two main design steps are applied to achieve the requirements of the SMPA. In the first step, the harmonic-termination biasing network using the NUTL is designed for the operating frequency as well as the second and the third harmonic. In the second step, the input matching and impedance transformation NUTLs are designed based on the optimum impedance of the chosen transistor and desired goals.

The design of the harmonic-termination biasing NUTL is carried out using S -parameter simulations. The resulting design is shown in Fig. 4a. The NUTL is simulated together with the bias voltage connection, a voltage stabilising capacitor, harmonic impedance stubs, and a tee junction to later connect to the transistor. The ports are placed at the tee junction as shown in the figure. The harmonic-impedance stubs are necessary to present a defined impedance at the harmonic frequencies at the load of the NUTL.

The NUTL parameters are set up for optimisation with two goals. Firstly, at the fundamental, *i.e.* 2.44 GHz in this design, the magnitude of S_{21} should be as close to 0 dB as possible to pass the energy through. Secondly, at the second and third harmonic frequencies, the magnitude of S_{21} should be as low as possible for high suppression. The simulated S -parameters after optimisation are plotted in Fig. 4b. Both optimisation goals are reached, with visible dips in S_{21} at the second and third harmonic, and a value close to 0 dB at the fundamental. The biasing network is used at the drain of the transistor. To simplify the design, the identical BN layout is employed at the gate.

The transistor footprint and model as well as the harmonic-termination NUTLs both at the gate and the drain side of the transistor are fixed in the simulation. A 6 W GaN HEMT transistor in a dual-flat-no-lead (DFN) plastic package from Wolfspeed/Cree (CGHV1F006S) is used, as it is characterised up to 15 GHz. The load-transformation NUTL and the input-matching NUTL are added to the simulation. The

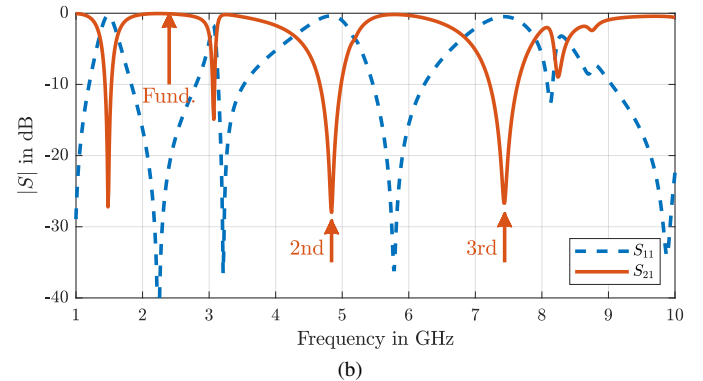
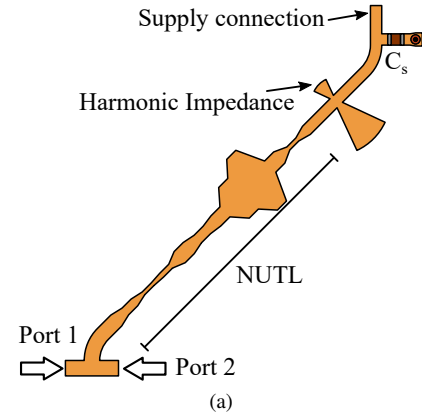


Fig. 4. (a) Layout and (b) simulated S -parameters of the harmonic-termination biasing NUTL.

parameters of the load-transformation NUTL are optimised to convert a $50\text{-}\Omega$ output load to the impedance at the drain of the transistor which delivers the optimum efficiency. The parameters of the input-matching NUTL are optimised such that the input impedance is $50\text{ }\Omega$.

The drain BN in parallel with the load-transformation NUTL forms the inverse class-F LTN. The simulated impedances presented to the drain of the transistor after optimisation are $21.25\text{ }\Omega + j53.95\text{ }\Omega$, $5.6\text{ }\Omega + j125.9\text{ }\Omega$ and $1956\text{ }\Omega + j1627\text{ }\Omega$ at f_0 , $2f_0$, and $3f_0$, respectively, for an inverse class-F SMPA.

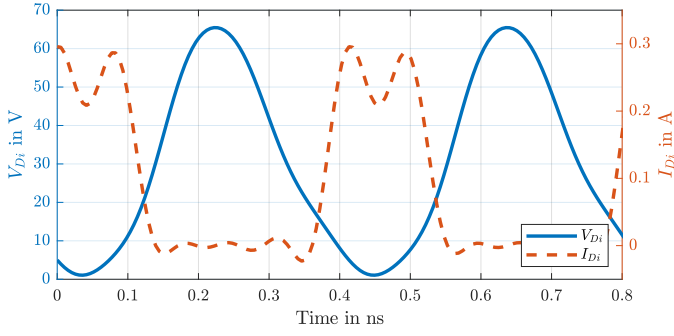


Fig. 5. Simulated drain current and voltage.

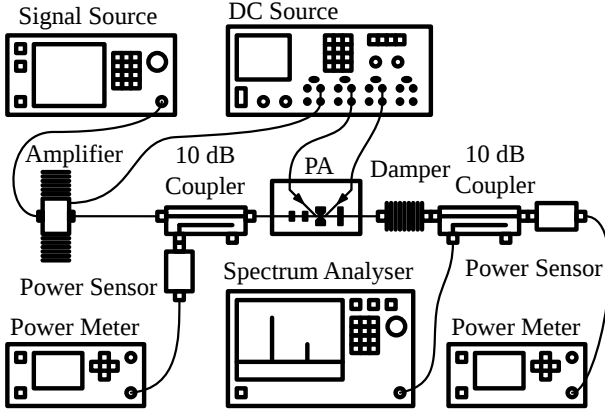


Fig. 6. PA measurement setup.

The layout resulting from the design process is shown in Fig. 3a. The simulated time-domain current and voltage at the drain of the transistor indicate the inverse class-F switching behaviour, as shown in Fig. 5.

III. MEASUREMENT RESULTS

The PCB implementation is done on a 0.76 mm thick Rogers RO4350b substrate, which is etched at the Chair of High Frequency Electronics Laboratory. The resulting PCB with a size of 10.9 cm × 5.1 cm is shown in Fig. 3b.

The measurement setup is illustrated in Fig. 6. The power coming from a signal source is preamplified and fed through a 10 dB directional coupler, to measure the exact input power using a power sensor connected to a power meter, to the DUT. The output power of the SMPA is fed through a damper and split up between a power meter and a spectrum analyser (SA), to observe the harmonic power and accurately read the output power, simultaneously. The measurement setup is controlled via GPIB and the measured S -parameters of the couplers and the damper are taken into account in the data analysis.

The simulated power-added efficiency (PAE) and gain over the input power, P_{in} , at a switching frequency, f_{sw} , of 2.42 GHz are compared to the measurement results in Fig. 7. The maximum efficiency point is shifted by 2 dB compared to the measurement. It is probably due to the transistor model. At higher input powers the trajectory of the gain is closely matched, and the PAE is slightly overestimated in simulation.

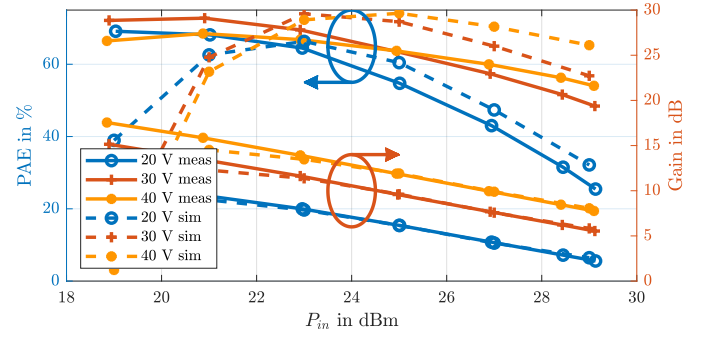


Fig. 7. Comparison of simulation and measurement results at various supply voltages.

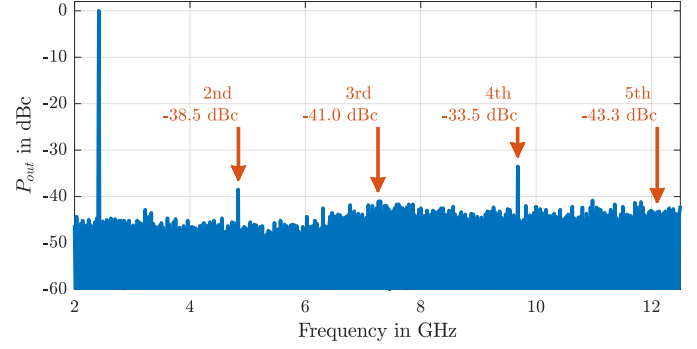


Fig. 8. Measured output spectrum of the SMPA.

The measured spectrum is plotted in Fig. 8. The power at the second harmonic is -38.5 dBc with respect to the power at the fundamental frequency of 2.4 GHz. This level of harmonic suppression is obtained due to the harmonic-termination BN and the LTN. The power at the third harmonic is not vividly distinguishable from the noise floor in the spectrum analyser.

The measurement is performed at ISM-band frequencies from 2.4 GHz to 2.48 GHz at 28 V drain voltage. The measured PAE and gain over input power and drain bias voltage are given in Fig. 9. Both PAE and gain deteriorate with increasing input power due to saturation. The drain voltage affects the gain linearly, while the PAE stays above 70 % from 24 V to 36 V at 21 dBm input power. Measured peak PAE is 72.7 % at an input power of 21 dBm.

In Fig. 10 the measured PAE normalised to the maximum is given over the frequency. It demonstrates a bandwidth within 0.9 from 2.3 GHz to 2.55 GHz. Furthermore, the power of the second harmonic is plotted, which is below 32 dBc from 2.35 GHz to 2.6 GHz, showing broadband harmonic suppression.

The performance of the designed NUTL-based SMPA is compared to literature in Table 1, where η is PAE. All other designs utilise a 10 W switching device, wherefore their output power, P_{out} , is higher. Various stub-based techniques for matching and harmonic termination are used. The efficiency as well as gain is comparable between all designs. It demonstrates the feasibility of the harmonic control only using NUTLs.

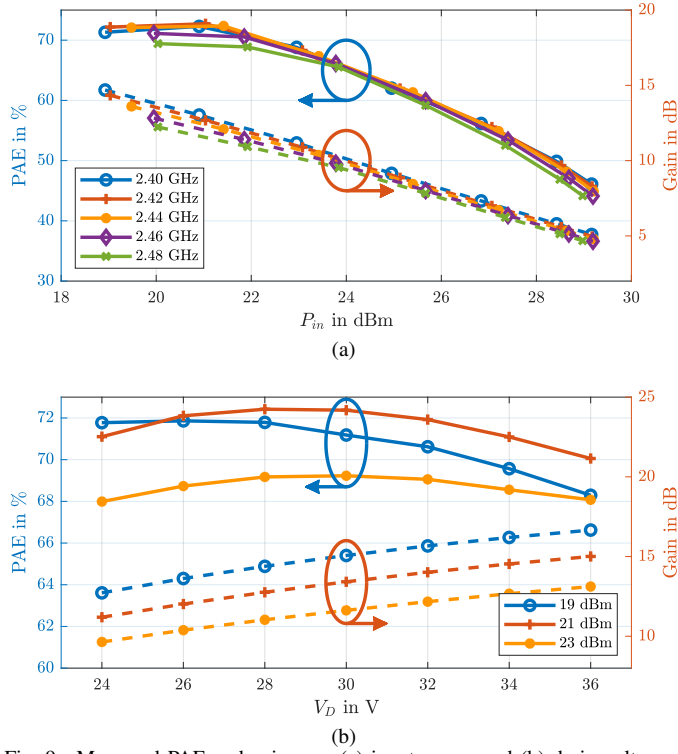


Fig. 9. Measured PAE and gain over (a) input power and (b) drain voltage.

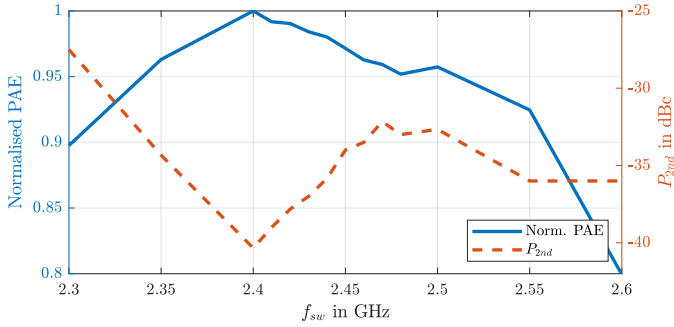


Fig. 10. Measured normalised PAE and the 2nd output power over frequency.

Table 1. Comparison of Inverse Class-F Designs.

	LTN	Device	η (%)	G (dB)	BW (GHz)	P_{out} (dBm)
This work	NUTL	CGHV1F006S	72.7 max	13.4 [†]	2.3 - 2.55	36.76
[8]	2-stage line-stub	CGH40010F	70 ^δ	13	1.4 - 2	40
[9]	multi-stage 2nd harm. control	CGH40010F	71 - 82 ^δ	10.1 - 11.5	1.35 - 2.35	40.1 - 41.5
[10]	Elliptic LPF	CGH40010F	68 - 82 ^δ	15.2 - 17	1.35 - 2.5	41 - 42.5
[11]	Harm. Load Pull	CGH60015DE [‡]	78 max	12 [†]	3.35 - 3.65	40.42

[†]At max η ; ^δDrain Efficiency; [‡] Bare Die

IV. CONCLUSION

We design and demonstrate for the first time, to the authors' best knowledge, a switching-mode PA utilising nonuniform transmission lines. The prototype demonstrates

a state-of-the-art PAE of 72.7 % at 2.42 GHz, 21 dBm input power and 13.4 dB gain. The proposed design method enables a measured harmonic suppression of -38.5 dBc and -41 dBc, at the second and third harmonic, respectively. Replacing 6 W GaN transistor to a high-power device, *e.g.* 10 W GaN, with the same concept is feasible. The PA can be used in a power efficient WPT transmitter in the future.

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