# A Compact and Power-Scalable 70W GaN Class-E Power Amplifier Operating from 1.7 to 2.6 GHz

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***Abstract*—A power-scalable, efficient and very wideband GaN class-E high-power amplifier is described. The large bandwidth performance is achieved by employing the so-called "class-E with parallel-circuit" loading conditions using a very compact all-lumped element implementation. The fundamental loading is realized by the magnetizing inductance of a novel bondwire-based transformer connected directly at the transistor drain. The PA input and output matching networks are entirely implemented with bondwire inductors and MOS/MIM capacitors. The amplifier provides an output power from 44 to 72W with a $PAE$ ranging from 60 to 69% ($DE$ of 64 to 71%) and a transducer power gain of 12.9±1.1dB over 39% bandwidth (1.75-2.60 GHz). The total area of the PA, including bias arrangements, 50Ω input and output matching networks, is only 2.9-by-1.7 cm$^2$.**

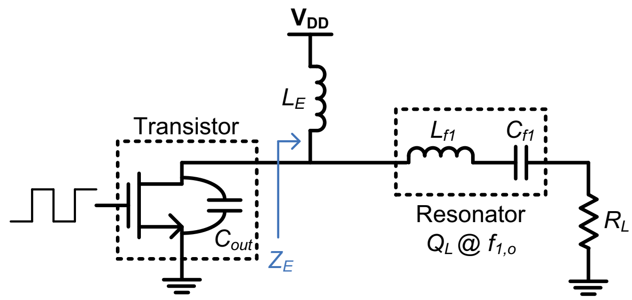
***Index Terms*—Bondwire, class-E, Gallium Nitride (GaN), power amplifiers, power transistors, transformer, wideband.**

## I. Introduction

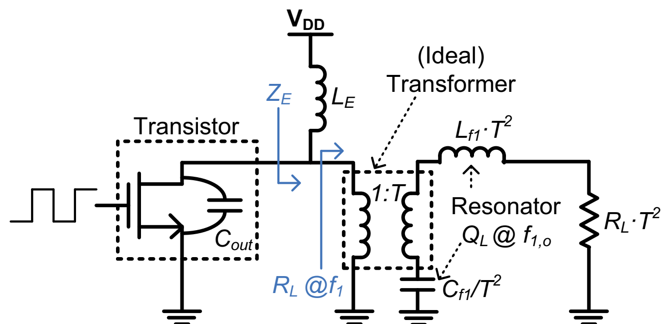
Due to the ever growing number of wireless services and subscribers, there is an increasing interest for wideband RF power amplifiers (PA) that allow cost reduction of future infrastructure networks. Those PAs must be highly efficient and linear to reduce power consumption and avoid spectral regrowth when handling 3G/4G modulated RF carriers with high peak-to-average ratios (PAR). Additionally, the form factor of the PA implementation becomes important for next generation transmitters that aim for remote radio heads, or even smart antennas.

Attractive high efficiency PA concepts for modern transmitters include Doherty and Outphasing [1] that make use of efficient PA units, where switch-mode PAs like class-E, F and F$^{-1}$ seem to be good candidates. Of these, class-E allows the simplest load network topology and can be implemented in a very compact area [2].

In this paper, we advance the developments for compact (i.e. aiming for all in-package) high-power wideband amplifiers by describing a 72W GaN class-E prototype with broader bandwidth than the design reported in [2]. The PA in this work allows easy package integration since it utilizes a bare transistor die surrounded by only lumped elements which are composed out of bondwire inductors and MOS/MIM capacitors for the matching networks. Additionally, this PA is truly power-scalable thanks to the use of a parallel-bondwire transformer [3] in the output matching network.




(a)




(b)

Fig. 1. Class-E PA with parallel-circuit output network: (a) topology proposed in [4], and (b) topology using a transformer.

## II. Wideband Class-E PA Design

In a class-E PA, an extra net reactance (generally inductive) is required in addition to the real load at the fundamental frequency while all the harmonics are opened (presented with high impedances). These loading conditions $Z_E(f)$ can be implemented in various ways due to the free-to-choose DC feed inductance $L_E$ [5], while various fundamental-tuned filter topologies can be used to present the open condition to the harmonics. In traditional "RF-choke class-E" PAs [6] $L_E$ is infinite and an extra reactance (named $X$) is placed in series prior to the filter. In the so-called "class-E with parallel-circuit" [4] $L_E$ is chosen finite such that there is no additional reactance needed in series with the filter. This later class-E implementation, depicted in Fig. 1(a), has important benefits over the first type: it is simpler, its optimum real load impedance is higher (or, equivalently, more power can be

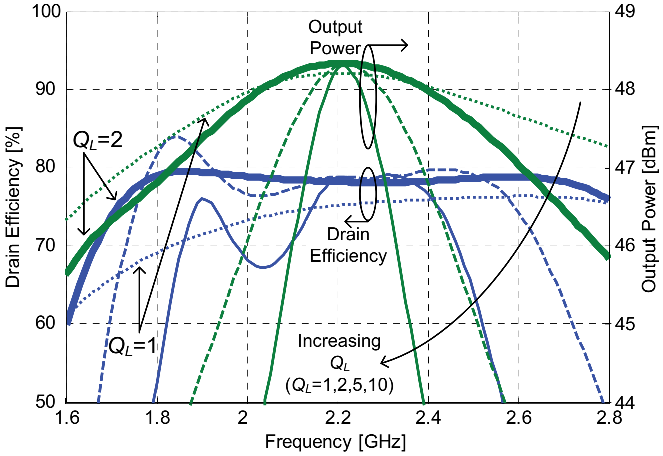



Fig. 2. Simulated effect of filter $Q_L$ on drain-efficiency and output power for the transformer-based class-E PA with parallel-circuit (Fig. 1(b)).

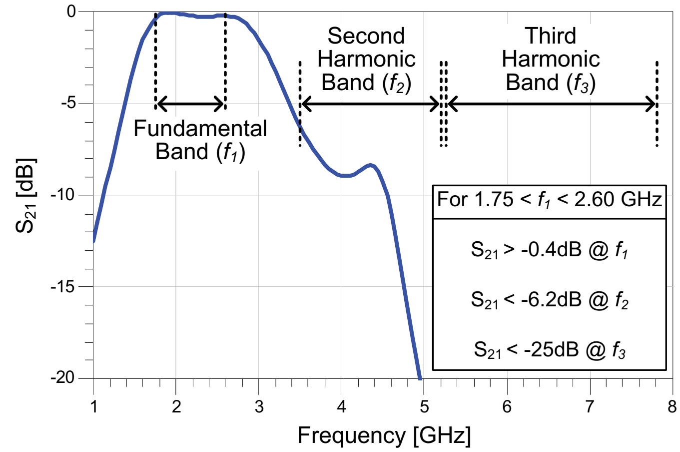



Fig. 4. Filter response of the amplifier output network including the transistor output capacitance (see Fig. 3), where port-1 is the real part of the transistor output impedance and port-2 is the system 50Ω impedance.

obtained for the same load) and it is more broadband in nature. The first two advantages are due to the fact that $X$ can be made zero, while the broadband performance also depends on the quality factor $Q_L$ of the filter. In this work, an alternative implementation of the class-E with parallel-circuit is employed by using a transformer. In this topology, depicted in Fig. 1(b), the $LC$ filter can be placed either at the primary or at the secondary side of the transformer (after proper impedance scaling). For very compact designs (e.g. all in-package), the use of a special transformer structure proves to be useful and facilitates true power-scaling in a natural way, as it will be explained in Section IV.

In practical class-E PA designs there is a trade-off between efficiency and bandwidth. When the filter $Q_L$ is high, the PA is narrowband and its efficiency is high. For very low values of $Q_L$, the PA is wideband but its efficiency is reduced by the losses related to the imperfect harmonic termination. In the case of the RF-choke class-E, for moderate to large values of $Q_L$ the high-efficiency bandwidth is roughly inversely proportional to $Q_L$ [7]. However, for the class-E with the parallel output circuit such a trade-off is greatly relaxed. In fact, in this later case, even for moderate values of $Q_L$, the bandwidth can be made broad with almost no efficiency degradation. As a practical demonstration of this fact, Fig. 2 shows the simulated performance over frequency (using a large-signal GaN transistor model and realistic transformer parameters [3]) for the square-wave driven GaN circuit of Fig. 1(b) for different values of $Q_L$ (1, 2, 5 and 10). For $Q_L$ from 10 to 2, the bandwidth of the PA is increased with no penalty on efficiency, while for $Q_L = 1$ the bandwidth is expanded at the cost of efficiency. For this reason, in this work a $Q_L$ of 2 was chosen to maximize the PA bandwidth.

The complete schematic of the implemented class-E PA is illustrated in Fig. 3. At the output side, a novel parallel-bondwire RF transformer [3] is connected at the transistor drain, whose electrical model is depicted in the figure for clarity. The transformer magnetizing inductance $L_p$ is designed to be equal to $L_E$, while any leakage inductance is absorbed by the filter inductance $L_{f1}$ (scaled at the secondary side of the transformer). Both sides of the transformer are AC-grounded, the primary side by a large decoupling capacitor while the

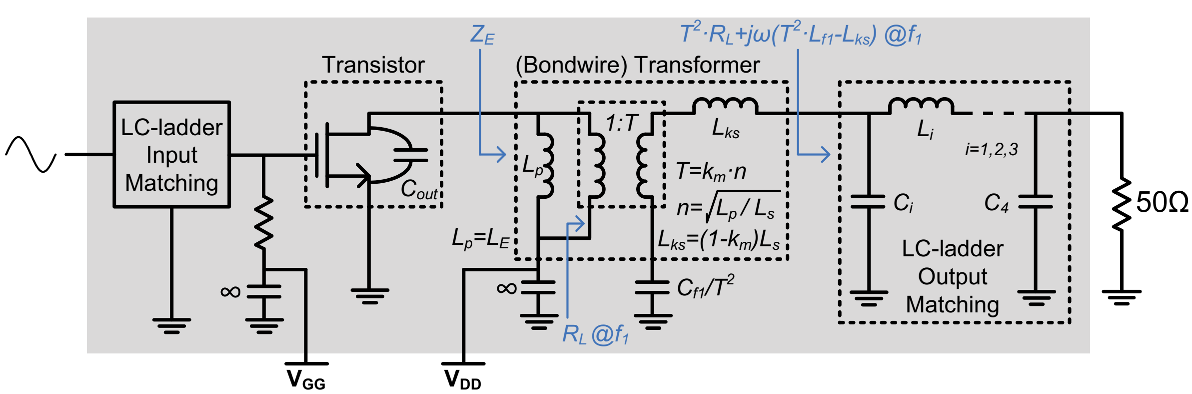



Fig. 3. Schematic of the implemented transformer-based class-E PA. The input side consists of an $LC$-ladder matching and a stability network. The output side consists of a (parallel-bondwire) transformer [3] followed by an $LC$-ladder matching network.

secondary side via the filter capacitance $C_{f1}$ (also scaled due to its location). A broadband $LC$-ladder output matching network (OMN) transforms the 50Ω system impedance to the optimum load $R_L$ plus any remaining reactance (if any) required by the $LC$ filter. At the input side, another $LC$-ladder input network (IMN) matches the transistor input impedance to 50Ω while an AC-shorted resistor near the gate stabilizes the transistor.

The frequency response of the series filter together with the OMN must be broad enough to provide a large RF bandwidth, but also must sufficiently suppress the harmonic bands. Fig. 4 shows the simulated "filter response" of the complete output network, including the transistor output impedance (Fig. 3). It can be observed that, between 1.75 and 2.60 GHz, the fundamental band is maintained flat (with a maximum deviation of 0.4dB), while enough suppression is provided at the harmonic bands (better than 6.2dB).

## III. Compact PA Implementation

The proposed PA is implemented using technologies familiar to the implementation of a standard packaged transistor. Both, 50Ω input and output matching networks are realized with bondwires and MIM/MOS pre-match capacitors, enabling a very compact design. A photograph of the implemented PA is shown in Fig. 5, while a cross-section of its output side is illustrated in Fig. 6. The PA employs a 14.4mm gate periphery GaN HEMT die, which was mounted on top of a 1mm-thick CuW flange. The shunt capacitors were placed on top of a 1mm-thick copper plate. Standard MOS pre-match silicon capacitor dies were used for most capacitors, while non-available (at the time of design) small values were implemented using MIM (parallel-plate) capacitors realized in a 2-layer PCB with 4mil-thick Rogers 4350B substrate. The same PCB substrate was used for placement of the biasing arrangements (SMD components).

The RF-path inductors were realized by placing several equal-shape 50um-diameter aluminum bondwires in parallel employing automatic bonding machines. The specific shape of each bondwire set (e.g., bondwire height, $BW\_H$, and length, $BW\_L$) was carefully designed for the desired inductance values (as in [2]) by using extensive Ansoft's HFSS (a full-wave 3D electromagnetic software) simulations. The transformer at the output of the PA (a parallel-bondwire transformer, PBWT, as described in [3]) was implemented by two coupled parallel bondwire sets, providing a magnetic coupling above 0.6 and very low losses in the order of 0.2dB ($G_{MAX}$ about 0.95). Due to this implementation approach, the PA effective area was only 2.9-by-1.7 cm$^2$, including all 50Ω input and output matching networks and bias arrangements, as shown in Fig. 5.

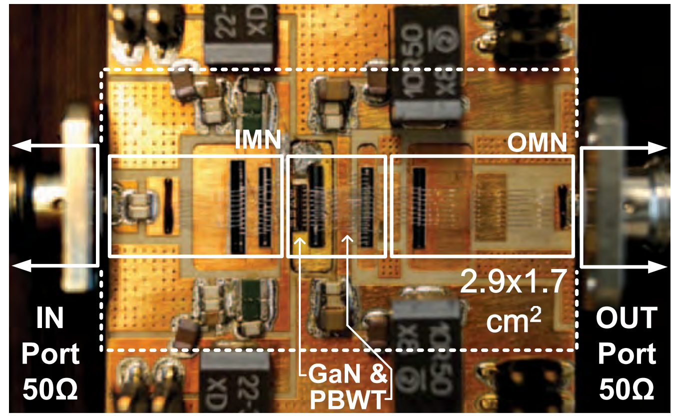


Fig. 5. Photograph of the implemented class-E power amplifier prototype.

## IV. Power-Scalable PA Implementation

Due to the physical properties of multi-wire PBWTs, the PA implementation is truly power-scalable. This can be explained as follows. To maintain class-E operation at different maximum output power levels (different sizes of the active die) the condition $q = 1/\left(\omega\sqrt{L_E \cdot C_{out}}\right)$ should remain constant [5]. Consequently, for a larger output power, the transistor die size will increase yielding increased $C_{out}$ and having proportionally more drain contacts. When utilizing these additional drain contacts for more paralleled wires in the PBWT, the magnetizing inductance $L_p = L_E$ will be roughly reduced by a similar amount as $C_{out}$ has been increased, keeping $q$ constant. Note that, if required, the bondwire height and length can be used for fine tuning the value of the PBWT's magnetizing inductance.

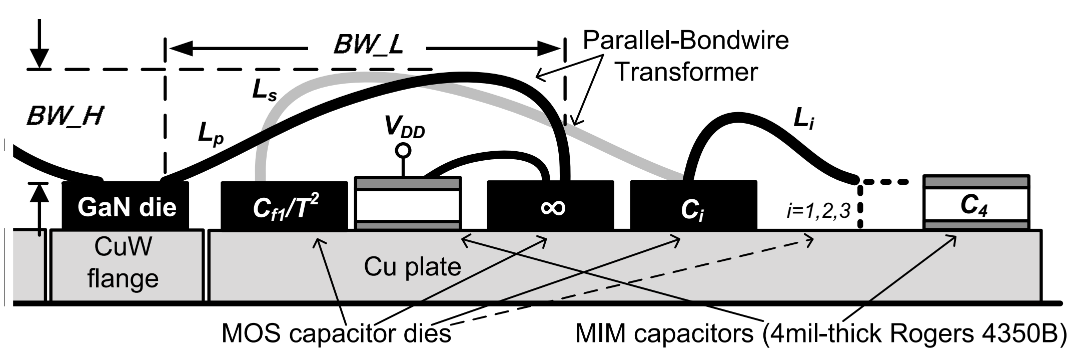


Fig. 6. Cross-section of the output network in the implemented amplifier (see Fig. 5).

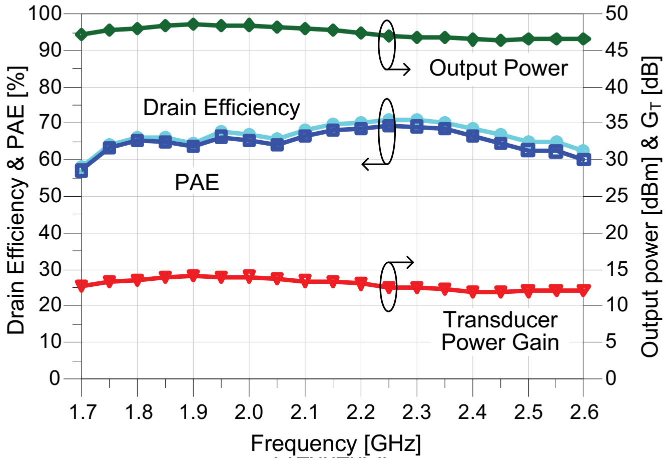



Fig. 7. Measured RF performance of the wideband class-E PA prototype.

TABLE I
COMPARISON BETWEEN (>1GHZ AND >5W) GAN CLASS-E PAS

| Work | Bandwidth [GHz] (%) | $P_{out}$ [W] | $PAE$ [%] |
|---|---|---|---|
| [8] | 1.80-2.30 (24%) | 3.2-5.6 | 52-57 |
| [9] | 2.05-2.25 (9%) | 15-20 | 60-71 |
| [10] | 2.00-2.25 (12%) | 74-112 | 65-71 |
| [11] | 2.00-2.50 (22%) | 7-13 | 71-74 |
| [2] | 1.70-2.30 (30%) | 42-65 | 63-72 |
| This work | 1.75-2.60 (39%) | 44-72 | 60-69 |

## V. MEASUREMENT RESULTS

The measured results of the implemented PA are shown in Fig. 7 for a supply voltage of 35V. This supply voltage guarantees a reliable operation of the GaN transistor as well as safe current levels for all the bondwires over the entire frequency band. The amplifier is driven with 34.5dBm (available) power, yielding about 3.5dB compression to enforce the transistor switch-like behavior. From 1.75 to 2.60 GHz (39% bandwidth), the PA reached an output power of 44 to 72W (47.5±1.1dBm), with a drain efficiency ($DE$) and a $PAE$ between 64 to 71% and 60 to 69%, respectively. In that band, the transducer power gain $G_T$ remained at 12.9±1.1dB. Table I presents the measurement results of this as well as other similar works on GaN class-E PAs (>1GHz and >5W output power) for comparison. It can be observed that this PA has a very favorable combination of output power, efficiency and form factor, along with a very large RF bandwidth.

## VI. CONCLUSION

In this paper, we presented a wideband PA based on a class-E topology with parallel-circuit loading, incorporating an ultra low loss bondwire-based transformer. It was shown that this topology can provide wideband performance without compromising the drain efficiency, as long as the quality factor of the series filter together with its harmonic suppression is optimized. A prototype amplifier was built to demonstrate this concept. Employing in-package technologies (such as a bare transistor die, pre-match capacitors and bondwire-based transformer and inductors) resulted in a very compact implementation. Additionally, through the use of a parallel-bondwire transformer, this class-E PA becomes truly power-scalable. The measured prototype showed a very large RF bandwidth with a very favorable combination of output power, efficiency and form factor.

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