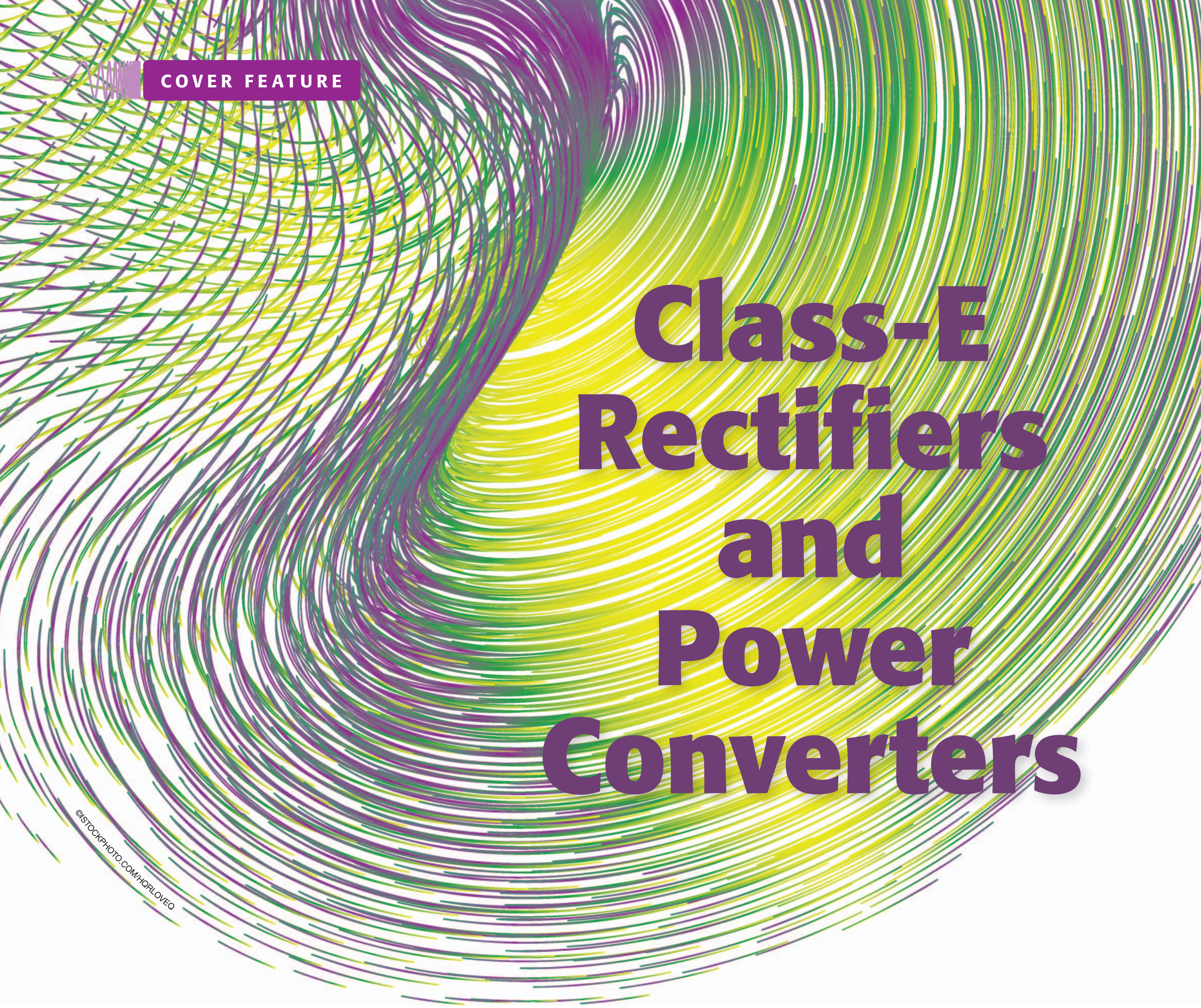

Class-E Rectifiers and Power Converters

José A. García and Zoya Popović

In the late 1970s, interest in reducing the value and size of reactive components motivated power supply specialists to operate dc-to-dc converters at hundreds of kilohertz or even megahertz frequencies. Passive energy storage (mainly magnetics) is the dominant factor in the size of power electronics and also limits its cost, reliability, and dynamic response. With the goals of miniaturization and improved control bandwidth, researchers had to face the frequency-dependent turn-on and turn-off losses associated with the use of rectangular waveforms in the hard-switched topologies of that time. Similar to approaches for RF/microwave power amplifiers (PAs), the introduction of resonant circuits allowed shaping either a sinusoidal voltage or current, with parasitic reactive elements absorbed by the topology in the neighborhood of the switching frequency. The resulting resonant power converters, obtained by cascading a

José A. García (joseangel.garcia@unican.es) is with the Department of Communications Engineering, University of Cantabria, Santander, Spain. Zoya Popović (Zoya.Popovic@colorado.edu) is with the Department of Electrical, Computer and Energy Engineering, University of Colorado, Boulder, United States.

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The experimental converter was designed and built with much less difficulty than the authors had expected, suggesting that the class-E topology was well suited to this application.

dc-to-ac resonant inverter with a high-frequency rectifier, first transform the dc input power into controlled ac power and then convert it back into the desired dc output [1].

In this article, we provide some historical notes concerning the operation of the class-E topology, which was introduced to the worldwide RF/microwave community by Nathan O. Sokal [2] as a PA (inverter) and a rectifier with very high conversion efficiencies up to microwave frequencies. We describe some recent research advances and implementations of class-E rectifiers and dc-to-dc converters at ultrahigh frequency (UHF) and beyond. We further highlight their potential in some modern applications, explaining their competitive performance in terms of efficiency for RF power recovery, together with a wide bandwidth for low-loss power conversion.

The Class-E PA/Inverter

A PA is called an *inverter* in power electronics or related areas [1]. When it is treated as an energy converter, effort is put into the dc-to-ac conversion efficiency rather than its gain. The input signal is usually the external excitation waveform required for properly driving its switching device. The need for such a signal may be avoided if an oscillator is employed in place of the PA .

Originally conceived in terms of an RF PA in [2], the idea of using a class-E topology for zero-voltage switching (ZVS) and zero-voltage-derivative switching (ZVDS) on the inverting side of a resonant power converter is attributed to Ronald J. Gutmann [3], a visiting member of the technical staff at Bell Laboratories in 1979 (on leave from Rensselaer Polytechnic Institute). A breadboard dc-to-dc converter, working at 10 MHz, was implemented, using a bipolar-based class-E PA (E10-3)—available by that time from Design Automation, Inc., Lexington, Massachusetts—and a shunt-mounted harmonically tuned rectifier with a silicon (Si) Schottky diode (Motorola 1N5822). After the class-E inverter was adjusted to optimize compatibility with the rectifier, an efficiency of 68% was measured, and load regulation capability with frequency control was successfully demonstrated.

A deeper insight into class-E power inverter operation was later provided in [4] and [5], coauthored by Richard Redl, Béla Molnár, and Nathan Sokal. Referred to as a *class-E converter*, a 40-W, 1.5-MHz implementation of the schematic shown in Figure 1(a) offered a high measured efficiency of approximately 85%. An International Rectifier IRF150 metal-oxide-semiconductor field-effect transistor (MOSFET) was employed as the power switch. The experimental converter was designed and built with much less difficulty than the authors had expected, suggesting that the class-E topology was well suited to this application. The 100-W, 14-MHz transformer-coupled converter illustrated in Figure 1(b), which was demonstrated in 1986 by Redl and Sokal [6], combined a high-power PA and a push–pull rectifier, with efficiency as high as 87%. Other significant contributions by the same authors are presented in [7] and [8].

Many subsequent examples of class-E power inverters may be found in the literature, including variants of the more traditional topology in [2]. This is the case, for instance, with the second-harmonic resonant class-E inverter presented by Keio University researchers in 1988 [9]. That topology is extended to a continuum of class-E topologies [10], many of which do not require an RF choke coil.

Implementations at high-frequency (HF) and very-high-frequency (VHF) bands

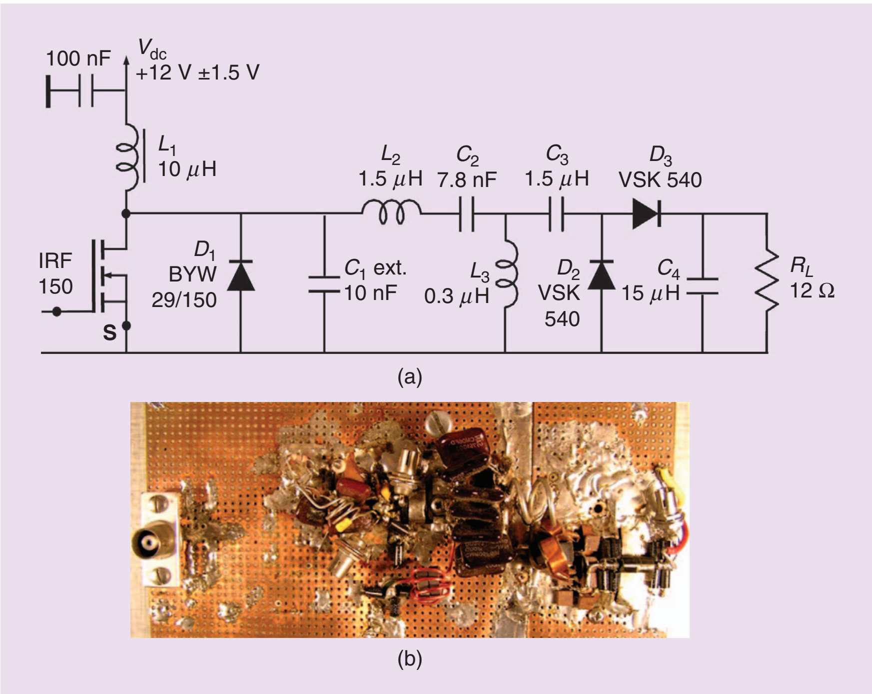

Figure 1. *(a) A schematic of the experimental converter in [4] (driver not included) and (b) a photo of the 100-W, 14-MHz converter in [6]. (Photo courtesy of Richard Redl.)*

have become common over the past two decades, with solutions based on class-Φ_2 inverters [11] highlighted for their high-efficiency, low-voltage stress and fast transient response performance. Figure 2(a) and (b) presents the schematic and a photo, respectively, of the inverter in [11]. The resonant leg formed by L_{MR}–C_{MR} imposes a low impedance across the switch at the second harmonic. Together with the remaining components, a quasi-trapezoidal drain-to-source voltage waveform is achieved with the desired low peak value, while near ZVS and ZVDS conditions are also maintained. A complete 110-MHz class-Φ_2 boost converter is shown in Figure 2(c) [12], with a power stage based on an RF laterally diffused metal-oxide-semiconductor (LDMOS) device and a Schottky rectifier complemented by a self-oscillating resonant gate driving circuit.

The approach was scaled to microwave frequencies as early as 1999 [13]. A low-power, 64%-efficiency, 4.5-GHz microstrip planar converter was demonstrated with an 86% efficiency gallium arsenide (GaAs) metal-semiconductor field-effect transistor (MESFET) class-E PA and an 83% efficiency Schottky diode rectifier, with the layout shown in Figure 3. When feedback coupling equal to the saturated gain of the PA is provided between the output and input, the class-E amplifier is converted to an oscillator with conversion efficiency equal to the power-added efficiency; this oscillator was used in [13] together with the rectifier to provide a dc-to-dc converter with no RF inputs and a slightly reduced efficiency of 57% at 725-mW output power.

Keeping frequency-dependent switching loss under control, the class-E circuit's soft-switching features have found use not only in high-frequency dc-to-ac power inversion but also in rectification.

Class-E Rectifier and Class-E² DC–DC Converter

Keeping frequency-dependent switching loss under control, the class-E circuit's soft-switching features have found use not only in high-frequency dc-to-ac power inversion but also in rectification. The ac-to-dc conversion is the time-reversal dual of dc-to-ac conversion, according to a principle described first in 1990 by Hamill [14].

Time-Reversal Duality

Any resonant amplifier may be transformed into a resonant rectifier of the same operating class according to the time-reversal duality principle. The rectifier switch voltage and current waveforms are time-reversed versions of the corresponding switch waveforms in the inverter,

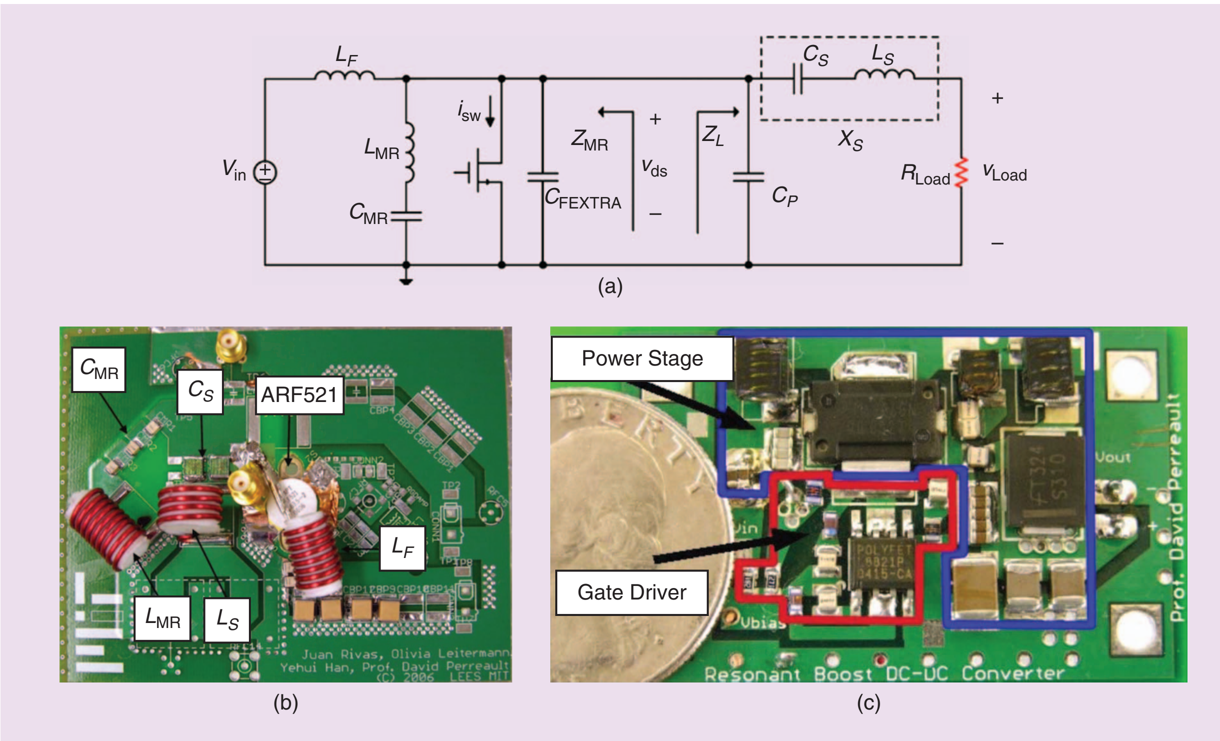

Figure 2. *(a) The schematic and (b) a photo of the 30-MHz class-Φ_2 inverter in [11], based on the ARF521 MOSFET from Microsemi. (c) A photo of a complete 110-MHz class-Φ_2 boost converter, with the output voltage control circuitry placed on the other side of the printed circuit board [12]. (Images courtesy of Dave Perreault, Massachusetts Institute of Technology.)*

Any resonant amplifier may be transformed into a resonant rectifier of the same operating class according to the time-reversal duality principle.

$$v_R(t) = v_I(-t), \tag{1}$$

$$i_R(t) = -i_I(-t), \tag{2}$$

leading to a simple relation between their instantaneous powers:

$$p_R(t) = v_R(t) \cdot i_R(t) = -v_I(-t) \cdot i_I(-t) = -p_I(-t). \tag{3}$$

Averaged over a cycle, the mean powers in these dual networks have opposite signs, indicating that the direction of energy flow is reversed in the rectifier for the desired ac-to-dc conversion.

Based on this, the class-E amplifier/inverter circuit in Figure 4(a) transforms to the class-E rectifier in Figure 4(b). Analyzed in detail in [15], this is one of the many possible topologies, with rectification of an active (or synchronous) type, in which the switching transistor's gate drive signal must be properly synchronized with the ac excitation. Under 50% duty-cycle operation and based on the remaining assumptions in [2], the class-E PA illustrated in Figure 4(a) is seen according to its drain voltage supply as a dc resistance $R_{dc} = 1/(\pi \cdot \omega \cdot C_p)$. For a dc load of this value at the output of the class-E rectifier [as in Figure 4(b)], a resistive input impedance is presented to the ac source equal to the well-known nominal terminating condition, $R_{ac} = 0.1836/(\omega \cdot C_p)$.

Under appropriate operating conditions, class-E rectifiers can work the same whether using diodes or transistors. However, at low output voltages, diode-based topologies exhibit lower efficiency due to the excess conduction loss caused by the forward voltage drop of a diode. While an active rectifier requires a driver circuit (which adds complexity and also consumes power), it may offer a unique capability for output voltage regulation [1]. Diode-based rectifier implementations are common at HF and VHF bands, but sufficiently fast Schottky diodes capable of handling high current and voltage levels are rarely available at UHF and higher frequencies, pointing to transistor-based rectifiers as the only choice for high-power RF-to-dc conversion at these bands. The intrinsic drain-to-gate feedback path in RF FET devices can be employed and may help avoid the need for the gate driving circuit.

Class-E² Resonant Converter

In [16], the class-E rectifier was conceived for the implementation of the double class-E, or class-E^2, resonant converter. As depicted in Figure 4(c), when cascading the circuits in Figure 4(a) and (b), the rectifier provides the load resistance R_{ac} required by the inverter. Therefore, both circuits may operate under the desired soft-switching conditions without additional circuit elements. For ideal lossless operation, the output dc voltage (V_{OUT}) would equal V_{DD}.

This converter was proposed with frequency-based output voltage control [16], following approaches similar to the pioneering work in [3]–[5]. The thinned-out method [17] [pulse-width modulation (PWM), or on/off] and phase-based techniques [18] are among other valid strategies for voltage regulation [19]. Up to the low VHF band, class-E^2 converter topologies usually incorporate diode-based rectifiers. The need for a gate-driving circuit on the inverter side or minimization of conduction losses in low-voltage and high-current applications has been addressed in these configurations. The solutions depicted in Figure 5 arise from the use of an oscillating inverter [20] or of multiphase topologies with interleaved cells [21], respectively.

While the synchronous operation of an active rectifier requires a second ac source to drive the gate of its transistor, self-synchronous operation is an attractive alternative for RF/microwave implementations. Relying on power coupled from the drain to the gate through the feedback capacitance, C_{gd}, and the use of a highly reflective termination at the gate [22], [23], the transistor may be turned on without a second source and with the same performance as that obtained for the optimum phase and amplitude of the synchronous drive signal—but with higher overall efficiency if the power of the drive signal is taken into account.

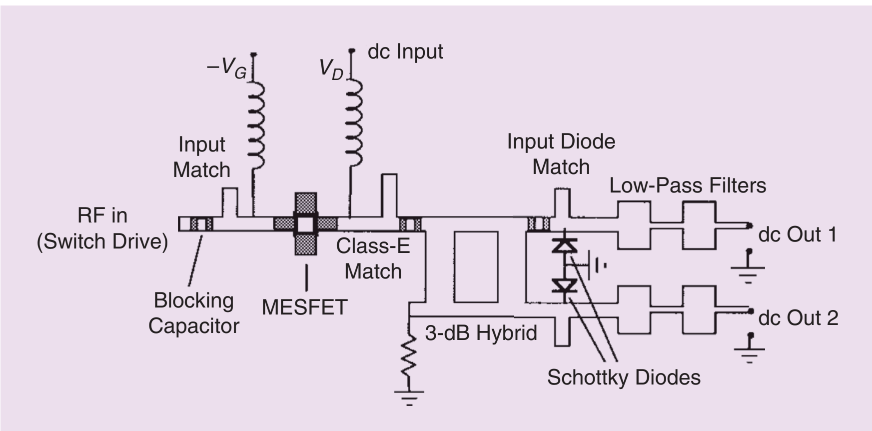

Figure 3. *The layout of a class-E dc–dc converter, switching at 4.5 GHz [13]. The converter uses a class-E inverter (PA) with a GaAs MESFET and a balanced microwave Schottky diode rectifier. It achieves 64% efficiency for a 3-V dc input and an 87-Ω load.*

Recent Applications and Design Examples

There is increased interest in class-E diode or FET-based rectifiers for efficiently recovering power from an incident RF signal in energy harvesting and far-field wireless power transmission (WPT) applications. As an example, a recent synchronous rectifier demonstrated in 0.13-μm complementary–metal-oxide-semiconductor (CMOS) technology at 2.4 GHz [24] is intended for wireless sensors that do not require batteries. A photo of the 850-μm × 870-μm rectifier die is reproduced in Figure 6(a), and the power efficiency and output voltage profiles versus the available power are plotted in Figure 6(b) for a load in the optimum conversion range.

Most of the rectifiers reported in the literature are the rectifying stages of the previously described double class-E resonant power converter. Class-E^2 topologies having a rectifier wirelessly connected to the inverter are also becoming common, at hundreds of kilohertz or a few megahertz, for implementing inductive or resonant WPT links. The Wireless Power Consortium and Power Matters Alliance WPT standards are based on the inductive coupling method, with a frequency adjustable from 87 to 357 kHz. In contrast, the Alliance for Wireless Power standard

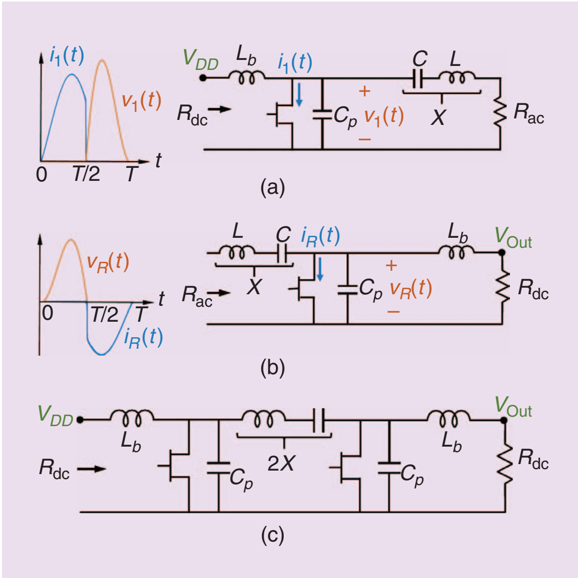

Figure 4. *(a) The class-E inverter, or PA, and (b) its transistor-based time-reversed dual, a class-E synchronous rectifier. (c) A basic class-E^2 dc-to-dc converter obtained when cascading (a) and (b). For operation at RF/microwave frequencies, the parallel capacitance (C_p) is generally provided by the device output capacitance (C_{out}). Characteristic waveforms for the switch voltage and current are also shown in (a) and (b).*

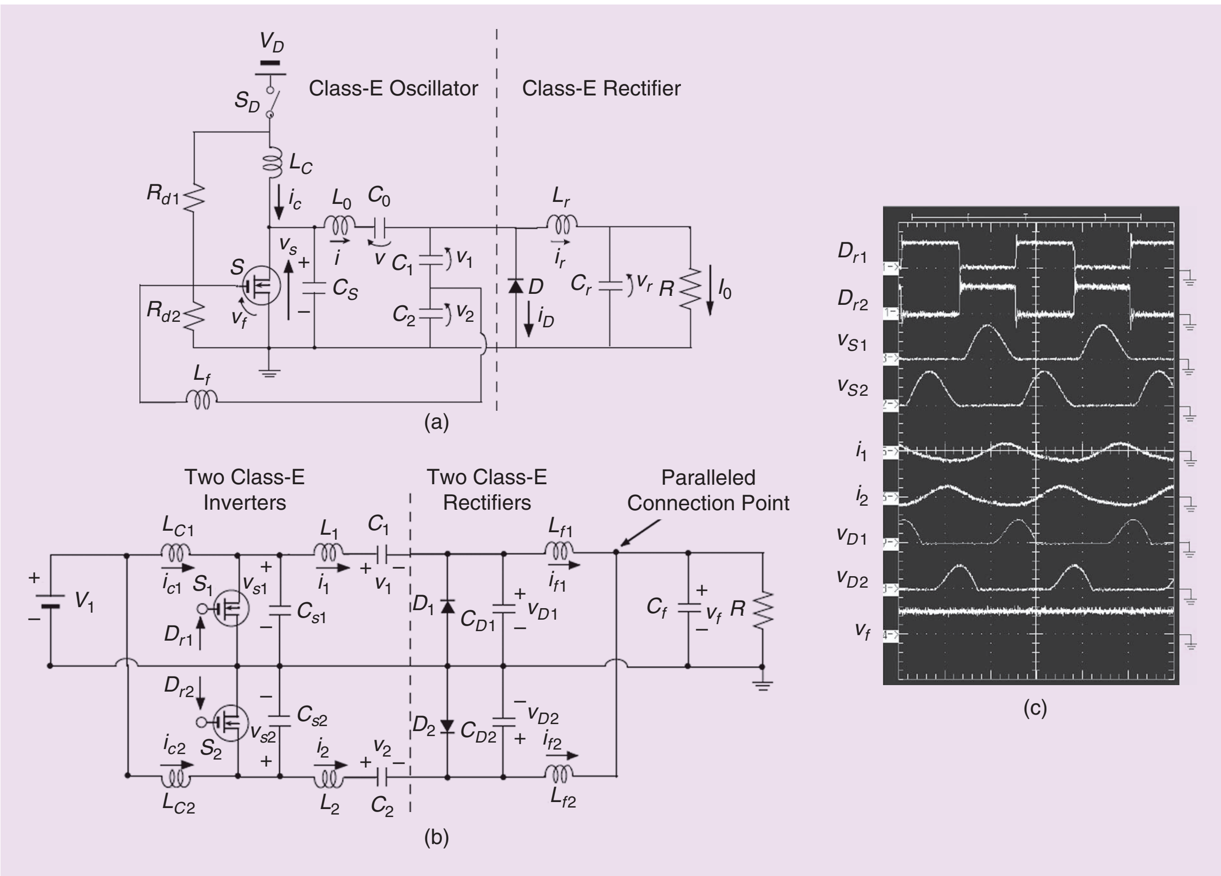

Figure 5. *The circuit topologies of class-E^2 converters as designed by Chiba University researchers: (a) a 1.55-W converter with oscillating inverter at 2 MHz (from [20]) and (b) a 3.2-W interleaved converter operating at 1 MHz (from [21]). (c) Experimental waveforms for the converter in Figure 5(b) (also from [21]).*

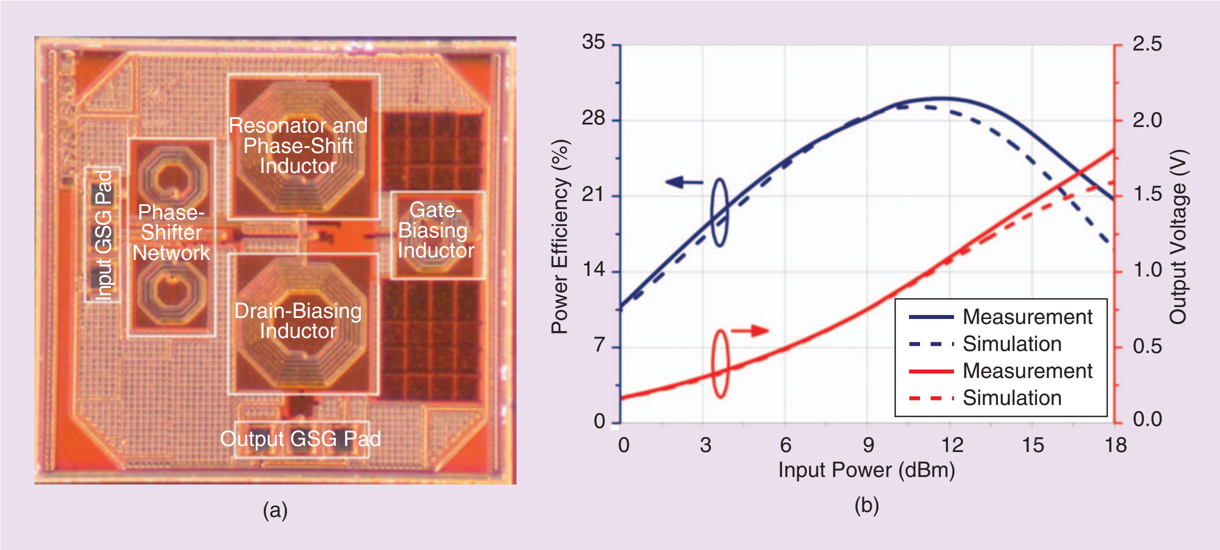

Figure 6. *(a) The class-E synchronous rectifier in [24]. (b) The power efficiency and output voltage as a function of available power at a 250-Ω load. (Images courtesy of Thomas Johnson, University of British Columbia.) GSG: ground-signal-ground.*

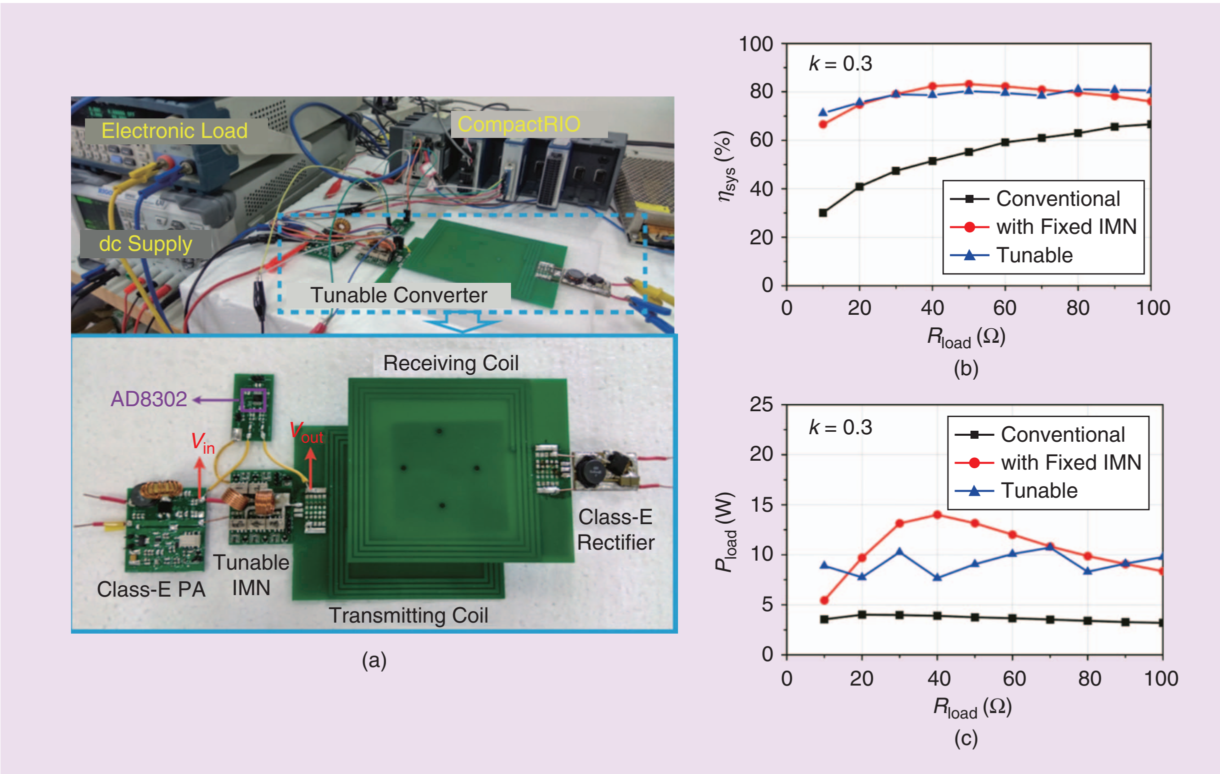

Figure 7. *(a) A dynamically controlled class-E^2 dc-to-dc converter at 6.78 MHz for WPT [26]. A comparison of (b) efficiency and (c) output power performance versus dc load with k = 0.3 for a conventional topology, a converter with a fixed-input matching network, and a tunable converter. CompactRIO: a real-time embedded industrial controller made by National Instruments; IMN: impedance matching network.*

employs the magnetic resonance method, with an operation frequency of 6.78 MHz [25]. Figure 7(a) presents an example of tunable class-E^2 converter application at 6.78 MHz [26], aimed at maintaining high efficiency while also ensuring stable output power under variable operating conditions (different coil relative positions and dc loads). A comparison of the measured efficiency and output power evolution with load resistance for a coupling factor (k) of 0.3 is shown in Figure 7(b) and (c) for purposes of illustration.

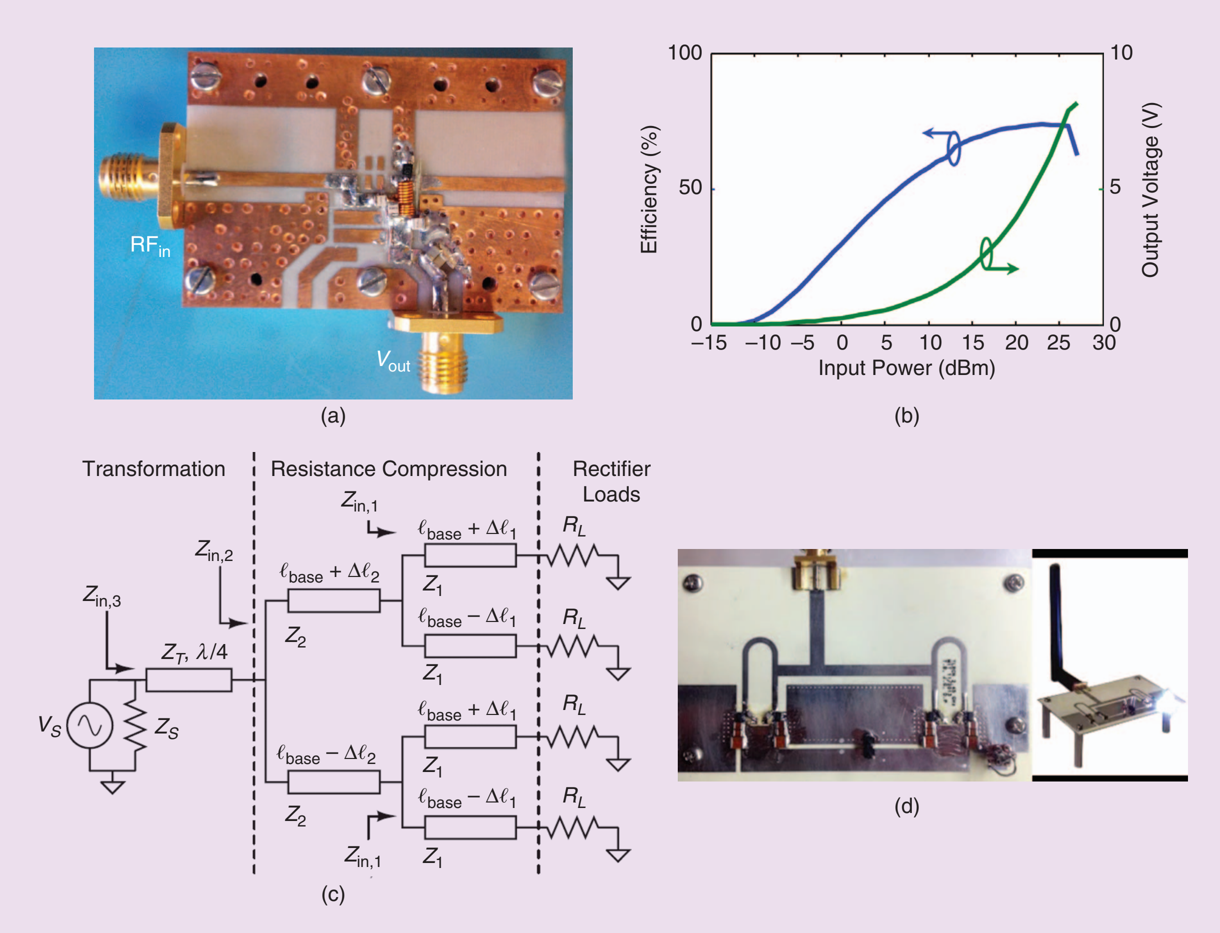

Figure 8. *The diode-based rectifier in [27]: (a) a photo and (b) the measured profile. The transmission-line RCN in [29]: (c) the schematic and (d) a photo. (Images courtesy of Dave Perreault.)*

Class-E Rectifiers

In this section, we describe two comparative examples of diode- and transistor-based class-E low-power rectifiers for use in far-field WPT. The class-E rectifier in Figure 8(a) from [27] employs an Avago Technology HSMS-282 surface-mount Schottky diode. A peak efficiency value of 74% was measured at 23 dBm [Figure 8(b)], with a recovered voltage linearly following the input amplitude. When the incident power is reduced, the variation in the input impedance affects performance. An interesting solution to this limitation may come from the use of a resistance-compression network (RCN) and a plurality of similar rectifiers. RCNs [28] are a special class of matching networks that provide reduced impedance variation at the RF input compared to that of rectifier inputs. A schematic and a photo of a four-way transmission-line RCN are presented in Figure 8(c) and (d), respectively [29].

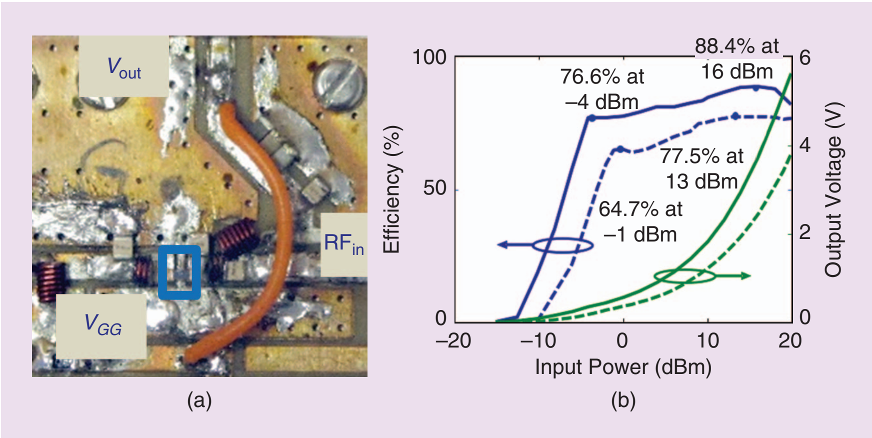

Figure 9. *The EpHEMT rectifier in [30]: (a) a photo and (b) the measured efficiency (blue) and output (green) results for 900-MHz (unbroken lines) and 2.45-GHz (broken lines) implementations.*

Figure 9(a) provides a photo of a self-synchronous and self-biased rectifier, using the VMMK-1218 EpHEMT from Avago Technology. A bootstrap connection of the rectified voltage to the gate terminal for turning on the

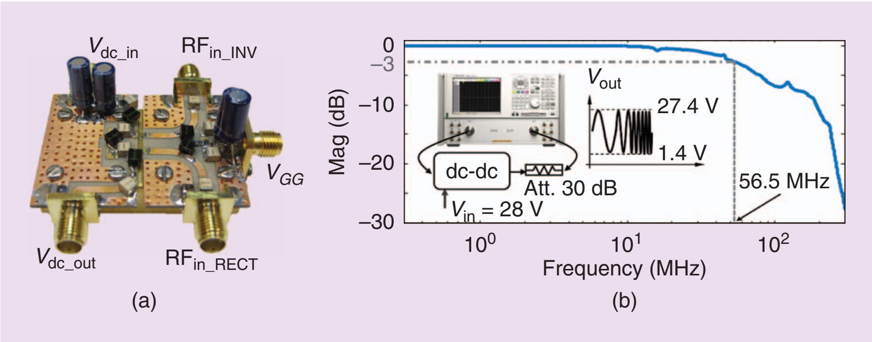

Figure 10. *A die-based GaN high electron-mobility transistor (HEMT) class-E² converter at 1 GHz: (a) a photo of the implementation and (b) the measured dynamic performance.*

device at very low power values is explained in [30]. The gate dc voltage can also be forced to follow the input power with an appropriately dimensioned biasing resistor and the small dc current resulting from rectification in the device gate-to-source junction. Measured results for 915-MHz and 2.45-GHz implementations in Figure 9(b) show high peak efficiencies (88% and 77%, respectively), with a reduction of only ten points for a power range of 20 dB.

A promising design methodology for class-E rectifiers with near-resistive input impedance was recently presented in [31]. Experimentally evaluated with Si Schottky diodes for VHF rectification, this method should translate well to transistor-based topologies at UHF and the lower microwave bands. An exhaustive performance comparison of recently reported RF rectifier circuits is included in [24], in which integrated and discrete rectifiers, following different topologies and based on either diodes or transistors, were studied. Including the previously discussed examples, class-E circuits have proved to offer competitive efficiency figures for RF power recovery.

DC-to-DC Converters

The examples of UHF/microwave converters discussed in this section include synchronous and self-synchronous rectifiers, along with an oscillating inverter (as in [13] and [20]). The photo and results depicted in Figure 10 correspond to a synchronous class-E² converter using CGH60030D gallium nitride (GaN) transistors from Wolfspeed, designed following the technique in [32]. With a peak of nearly 80%, the efficiency is as high as 75% for 6 dB of power backoff. Conceived to be employed with frequency-modulation (FM) control, as in [3]–[5] and [16], it can be used as an envelope modulator in an efficient supply-modulated transmitter. Very fast dynamic performance was measured, with a large signal bandwidth of 56.5 MHz and a slew rate 2.25 V/nS [33], the apparent state of the art for resonant power converters.

In Figure 11(a), a self-synchronous converter requiring only a single RF input is presented [23]. Implemented with Qorvo 250-nm GaN HEMT devices around 1.2 GHz, with a resonant dc-isolated coupling network between the PA and rectifier, 75% total efficiency is demonstrated at 5 W [Figure 11(b)]. An oscillating and self-synchronous dc-to-dc converter was also successfully demonstrated and tested in [23]. A photo of this converter is provided in Figure 11(c). As Figure 11(d) shows, 80% total efficiency was measured with a linear, frequency-based output voltage control available through the gate-to-source biasing voltage of the inverting device [34].

In [35], a class-E² architecture was also integrated in the Qorvo 150-nm GaN-on-Si carbide (SiC) process at 4.6 GHz, with decreased efficiency due to the increased losses expected at this frequency for this particular process. Nevertheless, this 2.3-mm × 3.8-mm integrated converter is fully monolithic, with no external magnetic components (Figure 12). The total efficiency of approximately 50% indicates that both the rectifier and amplifier are operating at efficiencies above 70%.

Some of these GaN HEMT-based double class-E converters have been integrated with class-E amplifiers [36] to implement polar transmitters. Figure 13(a) presents a version with packaged devices from Cree, using PWM or on/off control for the envelope coding [19]; the spectrum resulting from the reproduction of an Enhanced Data Rates for Global Evolution (EDGE)signal is shown in Figure 13(b). An average efficiency of 46% was measured.

Figure 13(c) presents an alternative implementation with dies, also from Cree and based on FM coding of the envelope. This architecture integrates a converter based on the one in Figure 10, later improved in [33]. The RF PA, originally designed as class-E amplifier, may be modified to class-J mode for operation in a hybrid envelope tracking/envelope elimination and restoration mode. An auxiliary GaN HEMT was added to reduce the sensitivity of the class-E² converter to load variations. The spectrum of the reproduced one-carrier wide-band code-division multiplexing access (WCDMA) signal is depicted in Figure 13(d). An average efficiency of 57% was measured in this case.

Conclusions and Expectations

The inherent low-loss operation of the class-E topology, introduced worldwide to the RF/microwave community by Nathan O. Sokal, has found significant applications not only in amplifiers but also for RF-to-dc and dc-to-dc power conversion [33]. Efficiency values reported for low-power transistor-based class-E rectifiers (designed for RF energy recovery at the 915-MHz and 2.45-GHz industry, medical, and scientific bands) are close to 90% and 80%, respectively.

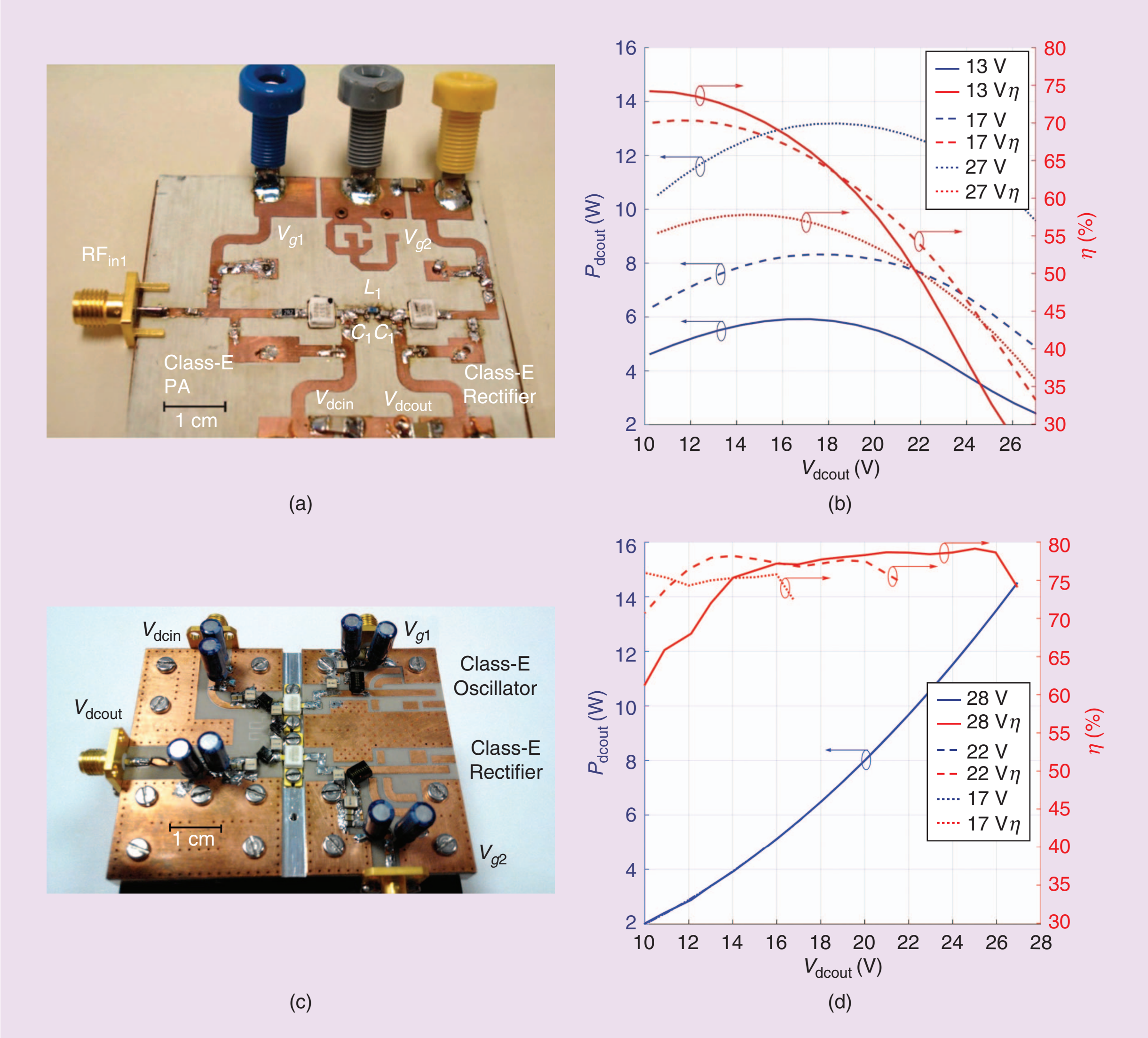

Figure 11. *A class-E^2 self-synchronous converter at 1.2 GHz [23]: (a) a photo and (b) the measured output power and efficiency profiles with output dc voltage. A class-E^2 oscillating and self-synchronous converter at 1 GHz [23]: (c) a photo and (d) the measured output power and efficiency profiles with output dc voltage.*

Interestingly, the synchronous and self-synchronous class-E operation and time-reversal duality of amplifiers and rectifiers extends to all amplifier classes. Efficient high-power rectifiers operating in classes E, C, F, and F^{-1} are demonstrated in the UHF and microwave bands using GaN HEMT hybrid technology [22], [37]. Single-ended, single-stage power-combined and two-stage GaN monolithic microwave integrated circuit (MMIC) implementations at the X-band have also been demonstrated, with efficiencies up to 70% [38], [39] at several watts of output power in harmonically terminated PAs operated as rectifiers (as discussed theoretically in [22]).

The integration of inverters (PAs) and rectifiers in double class-E power converters was discussed through several hybrid UHF and MMIC microwave experimental examples. Applications include high-efficiency inductive or resonant near-field WPT links

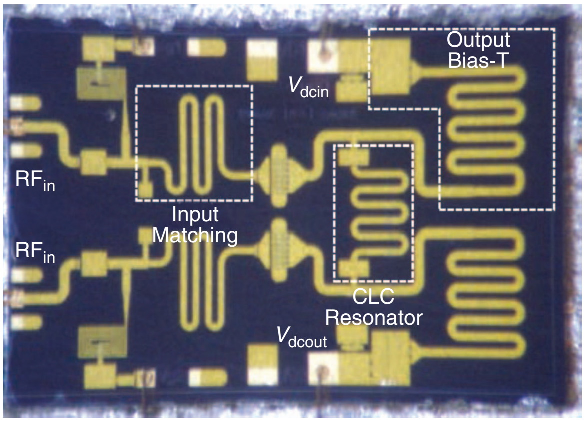

Figure 12. *A fully integrated class-E^2 synchronous dc-to-dc converter at 4.6 GHz [35]. The 3.8-mm × 2.3-mm GaN-on-SiC die using the Qorvo 150-nm gate process demonstrates a total efficiency above 50% with no external components. CLC: capacitor-inductance-capacitor.*

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and fast-response dc-to-dc converters. The operation of converters at higher switching frequencies is mainly motivated by interest in miniaturization and improved control bandwidth.

The frequency dependence of gating, switching, and magnetic losses imposes significant constraints on this progress [40]. Resonant gate driving and soft switching represent fundamental techniques to minimize these device loss mechanisms, which is one reason that the RF design concepts behind ZVS and ZVDS class-E PAs have been so attractive for power electronics specialists. Sufficiently fast switching may also help minimize or even eliminate magnetic materials [40], enabling not only printed circuit board but also MMIC integration of the power converter [35].

Table 1 provides a performance comparison of recently reported RF dc-to-dc converters. All of these are research-oriented implementations, and the authors are not aware at the time of writing of any actual uses of the class-E power converter in products. Although far from being competitive (in terms of conversion efficiency) with well-established kilohertz topologies, high-frequency class-E-based or -derived power converters may provide efficiency values close to 90% at 110 MHz [12], 80% at 980 MHz [23], and 65% at 4.5 GHz [13]. The power density may be far from the expected in research-oriented hybrid implementations, as in [23], but miniaturization up to the MMIC level has been shown feasible [35]. Wide bandwidth values and slew rates have been reported in the state of the art for switching converters.

The limitation in the measured efficiency at UHF and microwave bands may be partially attributed to

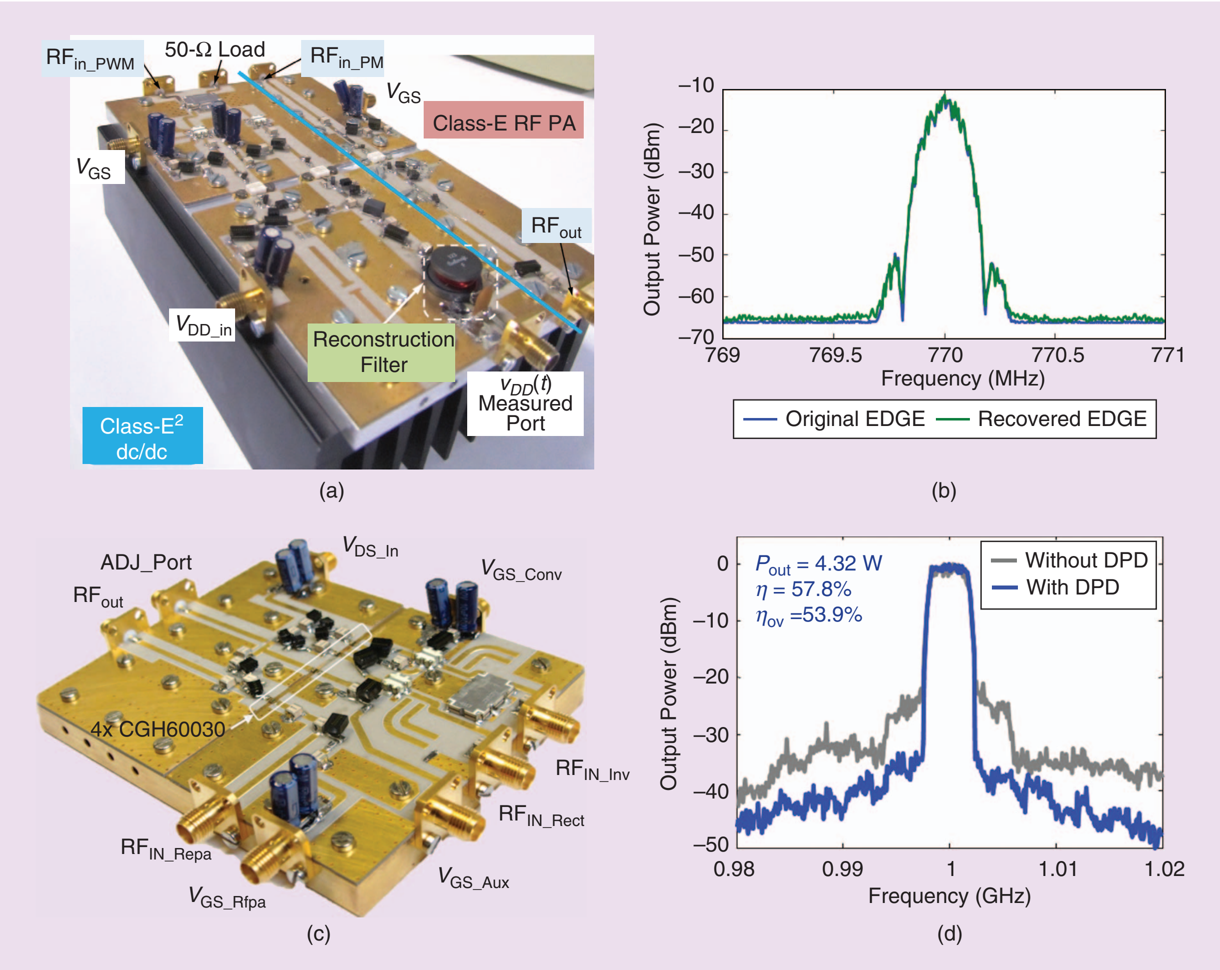

Figure 13. *Polar transmitter implementations integrating class-E² resonant converters: (a) a packaged device version at 770 MHz (from [19]) and (b) the reproduced EDGE signal spectrum. (c) A die-based architecture at 1 GHz producing a one-carrier WCDMA signal, as shown in (d). DPD: digital predistortion.*

TABLE 1. A performance comparison of recently reported RF power converters.

Reference	Frequency (MHz)	P_{out} (W)	η_{ov}(%)	Technology	Type	BW_{3dB} (MHz)	Size (mm × mm)
[21]	1	3.2	90	MOSFET	Interleaved class-E^2	N/R	N/R
[20]	2	1.55	78.9	MOSFET	Class-E^2 (with oscillating inverter)	N/R	N/R
[41]	20	16	92.5	GaN	Synchronous buck converter	N/R	2 x 2
[42]	25	68	96.5	GaN	Four-phase synchronous buck converter	20	N/R
[43]	30	220	87.5	MOSFET	Class Φ_2	N/R	N/R
[44]	100	7	91	GaN	Synchronous buck converter	20	4 x 4
[12]	110	25	87	LDMOS	Class Φ_2 resonant boost converter	1	27 x 49*
[45]	233	0.55	82	CMOS	Integrated buck dc–dc converter	N/R	3.5 x 4.5
[41]	400	5	67	GaN	Synchronous buck converter	N/R	2 x 2
[19]	780	11.5	72	GaN	Class-E^2	11	144 x 88
[23]	980	12.9	79.4	GaN	Class-E^2 (no RF inputs required)	32	60 x 77
[33]	1,090	8.5	76.7	GaN	Class-E^2 (with self-synchronous rectifier)	56.5	44 x 35
[23]	1,200	5	75	GaN	Class-E^2 (with self-synchronous rectifier)	N/R	56 x 60
[13]	4,500	0.053	64	GaAs	Class-E (with oscillating inverter)	N/R	140 x 70
[35]	4,600	0.6	48	GaN MMIC	Class-E^2	N/R	3.8 x 2.5

*As estimated from the photo; N/R: not reported. BW: bandwidth.

the fact that the employed RF transistors have not been fabricated for this purpose but rather for use in class-AB current-source PAs. The estimated losses for the 980-MHz converter in [23] showed that the biggest contributor to the dissipated power was the transistor's on-state resistance. Significant advances in high breakdown technologies, the optimization of the device layout for soft switching operation, and selection of the most appropriate architecture and control method [40] may all lead to further improvements.

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