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The class-E amplifier [1], [2], is a member of the switch-mode amplifier family. Switch-mode amplifiers are characterized by their use of transistors, instead of current sources, as switches [3].

Employing switching mechanisms in power amplifiers (PAs) at high frequencies was a concept hard to imagine even a few decades ago. The solid-state devices available to RF and microwave engineers in the 1970s and 1980s were slow and exhibited low power gain, and switch-mode operation of transistors was considered appropriate only for “low-frequency” power supplies, not RF power amplification. It was also difficult to obtain reasonable performance in some conventional approaches, such as class-C.

Switch-mode amplification circuits and theories are closely related to power-conversion circuits and systems, and most concepts used in switch-mode amplification are shared with power-conversion engineering. Consequently, many of the most relevant authors in the switch-mode (high-efficiency) RF amplification field have also had a background in power electronics and power conversion.

That is why it has taken so long for switch-mode high-efficiency amplification techniques to be widely accepted. Even today, there is some hesitancy about changing design approaches for many applications to use high-efficiency switch-mode amplification.

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Class-E Amplifiers and Applications at MF, HF, and VHF

Class-E and Switch-Mode Amplification

Traditionally, in the low-frequency range (up to 1 MHz), class-D amplifiers were preferred because of their efficiency and power capability. However, in many cases, the class-E amplifier is a better option because of its simplicity, cost, and size requirements: only one transistor and driver are used. And, as frequency increases, class-E is preferred to avoid the cross-conduction effect during switching times in two-transistor topologies (see “What Is a Class-E Amplifier?”).

Transistor parasitics can make it difficult to implement switch-mode amplification at high frequencies. In fact, the parasitics impose frequency limits on virtually all classes of operation. From a waveform point of view, transistor parasitics act as low-pass filters and eliminate the harmonic components required to operate in a determinate class of operation.

Class-E is designed to cope with the output shunt intrinsic capacitance of a power transistor, which is one of its most significant parasitics. That output shunt parasitic capacitance of a power transistor is used as a part of its load network, at least up to a determined maximum frequency.

Class-E is, in addition, relatively tolerant of slight load-impedance changes. The relatively simple output network is easily adapted to broadband operation. Class-E amplifiers can even operate beyond their maximum theoretical frequency for nominal (also called *optimum*) operation, with some efficiency degradation.

The principles of class-E operation are used in many other high-efficiency amplifiers. Some variations and related amplification modes (such as C-E, mixed-C, D-E, and E-F modes) have been used, sometimes unintentionally, as RF power engineers empirically improved the efficiency of their amplifiers [4]–[10]. For all these reasons, class-E is among the most popular and effective high-efficiency power amplification classes available today for RF and microwave power applications.

However, class-E also exhibits some drawbacks, such as high peak drain voltage and nonlinear behavior. These are being overcome by contributions from new solid-state and electronic technologies. Linearization techniques such as envelope elimination and restoration (EER), outphasing, and predistortion have been understood for several decades. However, over the past few years, there has been tremendous development of these techniques thanks to the latest advances in digital signal processing and circuit integration. These techniques can overcome the nonlinearities of class-E amplification (see “Modulating the Class-E Amplifier”).

In fact, the whole RF spectrum from several kilohertz up to 1 GHz can be covered using class-E switch-mode amplifiers, even in the nominal mode of operation [11]–[12]. Class-E amplification allows operational bandwidths of one octave, and even wider bandwidths [13] are possible if special circuits or some performance degradation is tolerated. This means, for instance, that virtually any application from 10 kHz

What Is a Class-E Power Amplifier?

Class-E refers to a single-ended RF power amplifier (PA) whose active device (transistor) is driven to act as a switch. The circuit (Figure S1) has an RF choke for dc feed, drain-shunt capacitance, and a series-tuned output. The series-tuned output circuit passes the fundamental-frequency current but blocks harmonic currents. In contrast, a class-B or class-C amplifier has a parallel-tuned output circuit.

For nominal (or optimum) operation, the series-tuned output is adjusted to produce a net inductive reactance X of $1.152/R$, and the drain-shunt capacitance (including drain capacitance) is adjusted to produce a susceptance B of $0.1836/R$. The resulting waveforms are shown in Figure S2. The drain voltage drops to zero and has zero slope at the instant the transistor turns on; thus, power losses associated with discharging the drain-shunt capacitance are eliminated. Because drain current flows only when the drain voltage is zero, the drain voltage is nonzero only when there is no drain current; if there is no discharge loss, the efficiency of an ideal class-E PA is 100%.

The essential design parameters are

$$\begin{aligned} P_o &= 0.577 V_{DD}^2 / R, \\ V_{D\max} &= 3.56 V_{DD}, \\ i_{D\max} &= 2.86 I_{dc}. \end{aligned}$$

In suboptimum class-E, the drain voltage drops to zero at the time of turn on, but the slope is not zero. When used as a linear amplifier, the PA reaches class-E operation only at peak output.

True transient class-E operation is possible at frequencies through VHF. At ultrahigh-frequency

Figure S1. A simplified class-E PA circuit.

Figure S2. The waveforms of an ideal class-E PA.

and higher, class-E operation is approximated by waveforms built from a finite number of harmonics.

up to 1 GHz at any output power level can benefit from this technology. With proper design, class-E can meet all technical requirements while simultaneously achieving considerable improvements in power efficiency compared to conventional amplification techniques. Additionally, industrial, medical, and scientific (ISM) applications can use class-E amplifiers to generate RF efficiently for a broad range of applications in the medium-frequency (MF), high-frequency (HF), and very-HF (VHF) bands.

In practice, the maximum frequency at which a device can switch is influenced by a combination of semiconductor technology, passives technology, and packaging and interconnection technologies. The maximum operating frequency of the class-E amplifier is limited mainly by the output capacitance of the switching device [14]–[15]. This capacitance is determined primarily by the semiconductor technology. Currently, frequencies in the gigahertz range are possible with gallium nitride (GaN) transistors.

Among all amplification classes, class-E is one of the most tolerant against transistor switching imperfections and exhibits smooth degradation with nonzero switching times and capacitances larger than the maximum required for nominal operation [16]. Suboptimum class-E operation is used when the semiconductor capacitance exceeds that for nominal operation. The drain efficiency degrades as frequency increases, but it is still a very good choice, even at three times the maximum frequency for nominal operation [17]. The boundary between nominal class-E and suboptimum class-E is sometimes not very distinct, and many so-called class-E amplifiers actually operate in the suboptimum mode.

Building Techniques and Components for Class-E PAs at HF and VHF

The proper selection of solid-state technology, circuit topology, components, and RF building techniques is crucial for achieving the high-efficiency goal in class-E amplifiers.

Building Techniques

Building techniques for high-efficiency switch-mode amplifiers such as the class-E amplifier are not different from the techniques used to build other classes of PAs for the same frequency band. Sources for good examples of proper building techniques for RF PAs include application notes from RF power transistor manufacturers, engineering bulletins, and amateur radio books and magazines [10], [18]–[22].

As a general rule, to keep the efficiency as high as possible, it is desirable to use low-loss load (matching) networks, including low-loss components exhibiting the highest unloaded Q possible. Some of the electronics components typically used in RF PAs in the HF/VHF range are shown in Figure 1.

Low-loss lumped components such as porcelain capacitors, air core inductors, and ferrite-loaded transmission-line transformers are commonly used in the HF bands. Inductors can be replaced by transmission lines (usually, microstrip-printed lines) at VHF and above, once their size is small enough to fit in printed circuit board (PCB) layouts.

Component parasitics are important at RF frequencies and become more significant for the high currents that occur in PAs. Another practical aspect to take into account is the peak voltage and current levels. It must be noted that peak voltage levels (as high as three or four times the power supply voltage) and high current must be expected in some points of the circuit. The power-handling capabilities of the transistors, passive components, and PCB traces must be considered and components chosen with adequate ratings.

Short circuits to ground are often required in PAs. However, they are extremely difficult to build properly at RF frequencies (on hybrid circuits using PCB substrates). Usually, arrays of plated-through via holes or plated slots are used to achieve the best possible short circuit with the least possible inductance.

An important aspect to take into account is providing the proper drive to class-E amplifiers (see “Driving the Class-E Amplifier”). For frequencies up to about 10 MHz, it is common to use square wave. At frequencies above the HF band, square-wave drive becomes impractical. This necessitates using a sinusoidal drive in spite of its lower efficiency. Circuit parasitics, especially those of the package and gate, impose constraints on the driving waveform and make the square-wave digital drive difficult or impossible. Additional discussion can be found in [23] and [24].

Transistors

From the 1960s to the present, the semiconductor technology for RF power applications has experienced slow but continuous improvement. Today it is possible to use transistors in switch-mode at high frequencies with good performance. Silicon solid-state technology allows

using switch-mode amplification up to high VHF and low ultrahigh-frequency (UHF) regions. Metal-oxide-semiconductor field-effect transistors (MOSFETs) and, especially, laterally diffused metal-oxide-semiconductor (LDMOS) devices are used with great success in the MF to UHF bands.

Gallium arsenide technology allows the building of high-efficiency switch-mode amplifiers up to the microwave region with low and moderate output power levels. Especially suitable for class-E operation, where high peak drain voltage is experienced, are the new wide-bandgap GaN and silicon carbide semiconductors, as they exhibit very good voltage breakdown performance. These recent solid-state technologies allow the use of switch-mode amplification techniques in the microwave region and at high power levels. This makes class-E competitive with other amplification technologies.

Capacitors

High- Q capacitors are crucial in RF PA circuits where impedances and currents are high and so power losses are potentially high. The most-used low-loss capacitor in a transistorized PA design is the porcelain multi-layer type. Several manufacturers provide low-loss capacitors that can provide unloaded Q above 500 or 1,000. Other capacitor technologies that are especially good in the HF to VHF ranges include mica dielectrics such as metal-clad mica and dipped-silver mica.

Dipped-silver mica capacitors work fine at HF and lower frequencies. However, they exhibit a low self-resonance frequency that makes them useless at frequencies above VHF. These capacitors can reach VHF only if their leads are kept short. In addition, they are relative large and expensive. Silver-mica capacitors have been mostly replaced in modern solid-state amplifiers by high- Q multilayer ceramic surface-mount device capacitors. These capacitors work acceptably from HF to UHF, are reasonable in cost, and have small footprints: they are still used in so-called low-frequency, high-voltage amplifiers [25].

Variable capacitors are not very common in PA designs. The more usual technologies are mica compression,

Figure 1. Typical components for PAs in the HF/VHF range.

Modulating the Class-E Amplifier

A true class-E power amplifier (PA) uses its transistor as a switch. It is, therefore, essentially fully saturated and unsuited to conventional linear amplification, in which the amplitude of the drive signal is varied to control the amplitude of the output signal. This is perfectly satisfactory for a number of applications that use constant-envelope signals such as FM broadcasting. However, most modern signals—including those used for cellular communication—employ signals with time-varying envelopes.

It is of, course, possible to vary the amplitude of the drive to the class-E output stage and thereby cause the amplifier to drop out of saturation and behave somewhat like a linear amplifier. The nonlinearity can be corrected by predistortion. However, the instantaneous efficiency drops with decreasing signal amplitude, just as in a class-B amplifier, resulting in a low average efficiency.

Linear amplification that maintains the high efficiency of the class-E PA over a range of amplitudes can be achieved by several techniques [S1], [S2], including

- envelope elimination and restoration (EER)
- envelope tracking (ET)
- outphasing
- RF pulse-width modulation
- load modulation.

EER amplifies the envelope and phase-modulated carrier separately, as shown in Figure S3. The amplitude modulation of the supply voltage in the final stage restores the envelope and thus recreates the desired signal. The envelope modulator must be highly efficient and is typically based on a class-S switching amplifier, class-G amplifier, or hybrid class-S/class-B amplifier. The class-E power converter has also been proposed for this application.

ET is used in combination with a quasilinear class-E PA. It is similar to EER but drives the RF amplifiers

Figure S3. A simplified block diagram of an EER system.

sapphire, glass, ceramic, polytetrafluoroethylene (PTFE), and air dielectric (piston and so forth), which provide reasonably high unloaded quality factors and current handling. Variable capacitors are used mainly in narrow-band amplifiers that require manual tuning and maintenance. Today, it is not common to see variable capacitors in new PA designs, especially modern broadband designs.

It must be noted, however, that, in RF practice, things sometimes work in unusual ways. For example,

capacitors can be deliberately used as inductances at frequencies beyond their series resonant frequency(!) [26].

Inductors

Air core inductors provide, in practice, the highest unloaded quality factors and are the favorite for PA design in the HF and VHF regions. Using low-loss plated-copper wire also contributes to keeping inductor losses low, but achieving quality factors above 150 or 200 is difficult. So inductors are usually the elements with the most losses in PA circuits, and designers try to avoid them when possible.

In the low-frequency range, inductors with cores need to be designed to avoid core saturation. Increased parasitics and losses pose a limitation in some applications. Magnetic design is key for success (again, a skill more common to power electronics engineers than RF ones). In Figure 2, some typical inductors (with and without cores) are shown for the HF/VHF ranges. Powdered iron is preferred for high-power applications, while ferrite is suitable for lower power [27].

Figure 2. Common inductors for the HF/VHF/UHF ranges.

for linear operation and maintains the supply voltage just above the minimum required for the instantaneous envelope.

Outphasing uses a pair of PAs (Figure S4) driven with signals of different phases. When the phases are the same, the two signals add and produce full output. When they are opposite, the two signals cancel one another and produce zero output. Thus, variation of the difference in phase controls the amplitude. Outphasing's

advantage over EER and ET is that bandwidth is not limited by the envelope modulator. With class-E amplifiers, the lengths of the lines to the combiner are adjusted to cause the amplifiers' load impedances to move on loci that provide good amplitude variation while maintaining high efficiency.

Varying the transistor's duty ratio in the class-E amplifier causes the amplitude of its output to vary, although not linearly. Thus, modulating the width of the pulses in the driving signal can produce amplitude modulation.

Another technique involves modulating the load impedance presented to the class-E amplifier. This is accomplished using one or more varactor diodes to

Figure S4. A simplified block diagram of an outphasing system.

vary the capacitance(s) in the load network. The load network must be designed so that the impedance locus provides both a good range of amplitude control and high efficiency.

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A side effect of inductor losses is the RF energy radiation. This can also pose a significant problem in meeting some electromagnetic interference or electromagnetic compatibility requirements.

Transformers

Transformers are very effective components for impedance transformation in PA design. Their main advantage is superior broadband impedance-transforming capabilities compared to other impedance-transformation technologies, such as discrete- or mixed-impedance transformation networks. They also allow the unbalanced-to-balanced transformation required by push-pull amplifier topologies. Figure 3 illustrates examples of transformers used in HF and VHF PAs.

At RF frequencies, different transformer technologies are used depending on the operating frequency of the amplifier:

- Magnetic-coupled transformers (discrete) can be used only at low frequencies, i.e., up to 30 MHz (monolithic microwave integrated circuits excepted), because of the limits their parasitics impose.

Figure 3. Common transformers for the HF/VHF/UHF ranges.

- Cable transmission-line transformers are used from low HF (3 MHz) up to high UHF (1,000 MHz).
- Low-loss RF cables (semirigid PTFE and the like) are used to implement these transformers because their length is still too great to be implemented using microstrip lines and their topology is not planar. Sometimes these transformers are loaded with ferrite cores to improve their performance at

Driving a Class-E Amplifier

Most published papers deal with the output circuit of the class-E power amplifier (PA). However, several techniques have been developed [S3] for driving class-E and other switch-mode amplifiers, including

- square wave
- untuned sine wave
- tuned sine wave
- harmonic enhanced
- transient shaped.

At frequencies of 10 MHz and lower, gate drivers can be used to produce square-wave drive. This generally allows the fastest switching and greatest efficiency.

Broadband class-E PAs operating at high and very high frequencies generally use sine-wave drive with gate-swamping resistors. Basically, a resistor placed from gate to ground serves as a well-defined dummy load for the drive signal. This allows the broadband transformer to do its job up to the frequency at which the reactance of the gate drops to lower than that of the gate-swamping resistor. It is necessary to overdrive the gate

somewhat to ensure the rapid turn on and turn off of the transistor.

At ultrahigh frequency and above, tuned sine-wave drive is most common. At these frequencies, the gate circuit exhibits resistance and reactance. The input matching network converts the gate impedance to something suitable for the driver amplifier. Again, overdrive is needed to ensure fast switching.

The switching characteristics can be improved and drive power reduced by using harmonic resonators to flatten the upper half of the driving waveform. This flattening is consistent with the flattening of the waveform by the diodes in a high-electron-mobility transistor.

Yet another technique shapes the drive waveform to resemble the current in the drain of the class-E PA. This provides the minimum necessary drive for all parts of the waveform without excessive overdrive.

Reference

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Figure 4. Examples of resistors for the HF/VHF/UHF ranges.

Figure 5. Typical arrays of plated via holes.

low frequencies (providing some magnetic coupling) and to achieve multioctave operation [5].

The transmission-line transformers typically used at microwave frequencies (quarter-wave, multisection, tapered lines) are not usually suitable in the low-frequency range because of their long wavelengths. However, their functions can be approximated by lumped-element networks [28].

Transmission Lines

At frequencies above UHF, transmission lines are used to replace inductors. (This is not common in the HF/VHF ranges.) Planar transmission lines printed on the amplifier PCB are usually employed, and microstrip transmission lines are the most popular by far. Because the lines are printed on the PCB substrate, the RF performance is critical. Bakelite or composite epoxy materials are not often used in PA design because of their high losses and poor RF performance. The popular glass-reinforced epoxy substrates such as FR-4 are successfully used up to the UHF region (usually below 700 MHz). At higher frequencies, the dielectric losses are unacceptable for many applications, and other substrate materials based on low-loss dielectrics such as PTFE or ceramics are mandatory. Gold or silver plating of the transmission line tracks is also important to reduce power losses while preventing corrosion.

Discrete capacitors are commonly used at frequencies below VHF. It is common to employ mixed networks containing lumped capacitors and printed lines at UHF and above.

Resistors

Resistors are unusual components in RF PAs, as they result in losses. Resistors are rarely found in the drain/collector or source/emitter paths but are common in the gate/base circuits. Resistors are also used for amplifier-stabilization purposes [25] or as balancing elements in combiners. At RF, resistors like capacitors and inductors

Figure 6. A 180-W class-E PA with details of the components. [Photo courtesy of the Radio Engineering Group (GIRA) at the Universidad Politecnica de Madrid.]

also show a resonance behavior (heavily damped) as frequency increases.

Standard carbon composition or thick-film resistors can be used in bias circuits because only dc current flows across them. Low-parasitic “chip” resistors (thick or thin film) specially designed for HF operation are mandatory for circuits where RF currents flow, such as feedback circuits or power combiners.

Figure 4 shows some RF power resistors used for PA applications.

Short Circuits

Short circuits to ground are usually required in PAs, but they are difficult to build properly at RF frequencies. The parasitic effects of short circuits are especially important because of the high currents involved in RF amplifier circuits. Arrays of plated via holes or plated slots are used to achieve the best possible short circuit, but some parasitic effects (especially inductive) cannot be avoided. Figure 5 shows a typical array of plated via holes on a power RF amplifier as well as several high-Q porcelain capacitors and an air core inductor.

PCBs

In RF and microwave circuits, the traces on a PCB act as transmission lines rather than simple connections. Interconnections between modules in rack assemblies also act as transmission lines because the lengths are a significant part of a wavelength.

As mentioned in the “Transmission Lines” section, the most popular dielectric material and laminates used in general electronics PCBs exhibit unacceptable losses

Figure 7. A 300-W (pulsed) class-E PA for radar applications. (Photo courtesy of the GIRA at the Universidad Politecnica de Madrid.)

at frequencies above UHF. This is especially problematic for high-efficiency PA applications that require minimum losses. Fiberglass-epoxy laminates such as the widely used FR-4 can be used up to low UHF bands, but low-loss dielectrics (usually based in PTFE) are recommended to achieve the best efficiency results from UHF and above.

Another important issue concerning this kind of amplifier is minimizing ground impedance. This is accomplished by using a proper ground plane in the PCB [25].

Figures 6–9 show several class-E amplifiers containing many of the high-Q components for RF power applications mentioned in the previous sections.

Examples of Class-E Amplifiers

Three amplifiers have been selected and included here as examples for the class-E technology in the HF/VHF/UHF bands.

Wide-Band 40-m HF-Band Class-E PA

The first example is a wide-band Class-E amplifier for the 40-m HF amateur band (Figure 10). This amplifier features a 60% fractional bandwidth at 7MHz, 90% peak drain efficiency, and 50 W of output power

Figure 8. A 300-W (continuous-wave) broadband PA containing ferrite-loaded transmission line transformers and RF resistors for feedback applications. (Photo courtesy of the GIRA at the Universidad Politecnica de Madrid.)

Figure 9. A broadband class-E PA for UHF mobile communications. (Photo courtesy of the Group of Power Electronics and Microelectronics at the University of Zaragoza.)

Figure 10. A wide-band Class-E PA for the HF band linearized by means of EER [11].

(Figure 11). It was designed by means of the admittance-synthesis technique, providing proper load for class-E nominal operation at the fundamental and harmonics [29]–[30].

The load admittance required to operate the transistor into nominal class-E is synthesized over almost one octave using a mixed-load network consisting of discrete components and a wide-band transmission-line transformer. An inexpensive silicon MOSFET for switching power applications is used as the active device. The amplifier is driven by a special wide-band

Figure 11. The output power, drain efficiency, and power-added efficiency of the amplifier in [11].

Figure 12. A wide-band class-E PA for the VHF band [37].

driver based on another class-E amplifier designed to decrease driving losses at high frequencies [31].

The entire amplifier is linearized by means of an EER system [32]–[36]. In Figure 10, the high-efficiency class-S amplifier section used for EER can be seen in the lower left.

Wide-Band VHF-Band Class-E PA

The second example is a wide-band class-E amplifier designed for the mid-VHF (FM broadcast) band [37] (see Figure 12). The amplifier features a 40% fractional bandwidth at 100 MHz, a 90% peak drain efficiency, and 150 W of output power (Figure 13). It is also designed by means of the admittance-synthesis technique.

Its relatively high output power (150 W), low supply voltage (28 Vdc), and transistor package parasitics make it difficult to synthesize broadband networks with the load admittance required at the “virtual” drain plane. Consequently, a mixed-load network consisting of lumped components and a transformer made of low loss semirigid coaxial cable is used to provide the required load to the silicon LDMOS packaged transistor used in the amplifier.

Figure 13. The measured (a) output power and (b) efficiency versus V_{dc} of the amplifier shown in Figure 12.

1-kW Continuous Wave Class-E PA

The third example (Figure 14) is a class-E amplifier designed by IXYS Colorado for the 27.12-MHz ISM frequency [21]. The circuit is a class-E amplifier demo board (also designed by IXYS Colorado) with 1,000-W continuous wave (CW) output power and efficiency better than 86% into a 50- Ω load. This is an excellent board to use for understanding the capabilities of IXYS MOSFETs for this application and learn about the possibilities of high-power class-E amplifiers in the HF range. Figure 15 shows the drain and output voltages for 1,000-W CW output power into a 50- Ω load.

Figure 14. An HF 1-kW class-E amplifier. (Photo courtesy of IXYS Colorado.)

These amplifiers are used in ISM applications such as RF heating, semiconductor processing, and the like. Another interesting example for 13.56 MHz is described in [20].

TABLE 1. Examples of class-E applications in HF and VHF.	
Application	Frequency
Broadcasting	AM: 500 kHz–1.6MHz (2.3 MHz–21.6 MHz)
Broadcasting	FM: 88–108 MHz
Ham radio	CW from 135 kHz and up, single sideband from 1.8 MHz and up, FM from 27 MHz and up
Mobile communications	AM, FM, and digital at VHF and UHF bands
RF identification near-field communication	ISM (125 kHz, 13.56 MHz, 433 MHz, 868 MHz, etc.)
Transcutaneous implants	AM, amplitude and frequency shift keying (100 kHz–1 MHz)
Wireless power transfer	CW (30 kHz–30 MHz)
Induction cooking and heating (industry)	CW (30 kHz–10 MHz)
MRI	Pulsed, 42–297 MHz
Radar and radio navigation	Several modulations from very low frequency and up

Figure 15. (a) Drain and (b) output voltages for the 27.12-MHz class-E amplifier. (Images courtesy of IXYS Colorado.)

Figure 16. (a) A 10-kW AM broadcast transmitter and (b) an E-class power module. (Photos courtesy of Broadcast Electronics.)

Typical Applications

The range of frequencies from 10 kHz to 1 GHz covers many applications where class-E topologies have been successfully applied in communications and ISM applications. Table 1 provides a brief review.

Two examples of such applications appear in Figures 16 (AM broadcast amplifier) and 17 [magnetic resonance imaging (MRI) amplifier]. The amplifier in Figure 16 is from Broadcast Electronics, one of the first companies to license class-E from Nathan O. Sokal. Their series E and series A transmitters provide up to 10 kW for the AM band (522–1,700 kHz) with 75% (or better) efficiency and 100% modulation by a sinusoid.

The amplifier in Figure 17 is was built by Green Mountain Radio Research Company (GMRR) and Communication Power Corporation (CPC). It uses

Figure 17. A 42-MHz, 700-W, 80% efficient EER transmitter for MRI. (a) An external view (chassis) and (b) a view of amplifier. (Photos courtesy GMRR and CPC.)

class-E amplifiers and EER to produce a 700-W MRI signal at 42.6 MHz with an efficiency of 80%. Each module contains two class-E PAs, two class-S modulators, and a combiner.

Final Comments

Class-E amplifiers have been successfully implemented from low frequencies through UHF using discrete passive components, transmission-line transformers, and discrete transistors. These amplifiers' outputs from watts to kilowatts with efficiencies of 70–90%. They can be adapted to linear operation through techniques such as EER, outphasing, and predistortion. Applications include broadcasting, amateur radio, RF heating, MRI, wireless power transfer, and HF–VHF communication of all types.

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