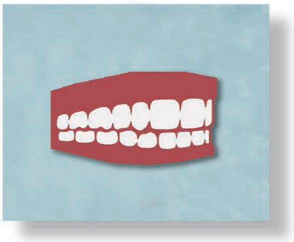
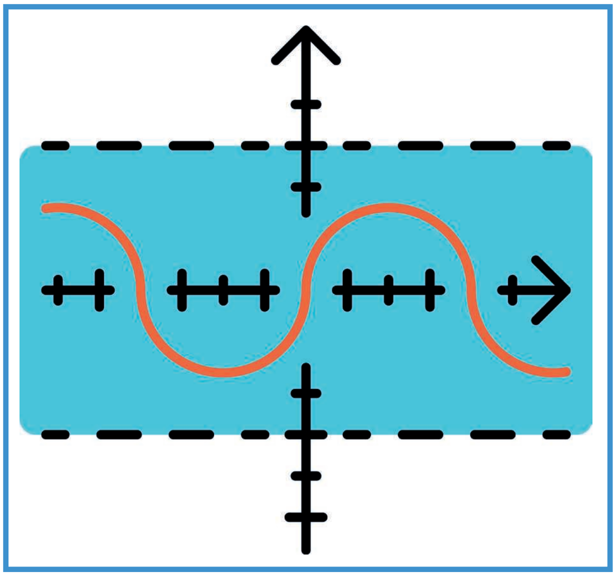


Microwave Bytes

Pushing and Pulling

■ **Steve C. Cripps**



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Well, it's been a while. The world gets crazier and more crowded, and nature's effort to put a stop to it all in the form of COVID-19 seems to be somewhat faltering around my own lockdown spot, but who knows what the next 12 months will bring. In the meantime, technical activity stutters along, largely without the distraction of measuring any hardware; simulation has finally taken over from reality.

I still work on RF power amplifiers (RFPAs), believe it or not. I have been at it for a few decades, but as time goes on, I find I seem to know less rather than more about the subject, which I suppose at least keeps the mind active, and as the years advance, this is a good thing. There are new things and new ideas around, some of which are actually not really new at all but reincarnations of older ways. But there is also a rather resilient set of old chestnuts, (concepts and misconceptions) that refuse to go away. The latter frequently arise from one of the "cultural differences" that seem to persist in the electronics world; I have in the past addressed the cultural divide between digital and RF, but even within the RF world as we now know it, there are cultural subdivisions. Some exploration of these would appear to be a good starting point for a column reincarnation.

Where to start? Like a preacher, which I hope I am not, I thought I would kick things off with some "text": in this case, a question that was asked of me recently when I was teaching a four-day course on RFPA design. The participants at these courses usually have quite a varied background, which, by about day three, one has fairly much characterized, and not always to the credit of certain, more "demanding" (e.g., irritating?) individuals. So as the morning coffee break approached, this individual, to whom I will refer as *PIA*, asked the following question: "Why don't you microwave guys design power amps properly, using transformers and push–pull?"

Hmm. Yes, this is indeed an old chestnut and one that I have been asked many times over the decades. (One of the questioners was myself, and it would possibly be of some interest, or maybe more likely entertainment, to examine my answers, which have undoubtedly changed over this extended time span.) Indeed, my immediate response has often been, "Do

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you want the one-word answer or the three-day seminar?"—which, of course, in this particular case, fell a bit flat given that the question was posed on day three of such a seminar. The one-word answer is "transformers." I have always said, and basically still do say, that conventional transformers don't work at gigahertz frequencies, and the slew of ingenious substitutes never really comes up to the mark. These days, however, even that gets questioned, possibly by the same PIA, inasmuch as there is a well-known manufacturer, much beloved of PIAs, that offers a plethora of RF transformers, some even specified into the low gigahertz region. Transformers also seem to reappear as a staple item in millimeter wave (mm-wave) RF integrated circuits (RFICs), particularly the CMOS variety. Thereby hangs another subcultural conflict that I plan to discuss in a future column, but for the time being, let's pick apart the basic issue a bit.

I have no doubt, none whatsoever, that the basic "push–pull" circuit is one of the great iconic circuit configurations of the electronic era. Its origins are a little obscure, as I described in a workshop session at the IEEE International Microwave Symposium in 2015 [1]. There are a few patents dating back to the turn of the 20th century; interestingly, the main contender was filed by Colpitts, of oscillator fame, in April 1915. One or two circuits even predated the vacuum tube, but certainly, by the 1920s, commercial audio amplifiers were being widely advertised and were clearly push–pull designs. Then, as now, the central issue was heat; power amplifiers need to be efficient for a number of reasons, whether it be the cost of the electricity or the longevity of the amplifying devices. I will at this point avoid a lengthy, or even abbreviated, diversion into PA classes; essentially, sometime very shortly after the invention of the triode vacuum tube, someone discovered that biasing the grid nearer to the cutoff point yielded a similar power output but consumed much less supply current and hence resulted in an improved efficiency. But a varying signal would be heavily distorted, rectified, in fact—welcome to the world of class-B amplification. The distortion problem could be largely mitigated, however, by using a differential arrangement, whereby positive- and negative-going signal excursions could be amplified by opposing devices, per the classical schematic shown in Figure 1. Even in 1920, it was possible to manufacture suitable transformers that performed well enough over the audio band of frequencies.

And so it still is; however, we are concerned with the *RF push–pull amplifier*, which is a derivative, rather than a direct descendent, of the basic classical audio configuration. There is an important difference in making the leap from audio hertz to RF megahertz—*in an RF application, the signal is sinusoidal.* As such, the basic action of the differential arrangement to preserve the complex broadband audio waveform is no longer needed. Indeed, at gigahertz frequencies, we can (and do, much to the chagrin of PIA and many others) use single-ended amplifiers biased at, or near to, the class-B condition, on the basis that the resulting "rectified" sinewave can be "converted" back to the original sinewave using a suitable filter. And there's the crux of the whole matter; this "suitable" filter ends up having a number of requirements that, depending on the application and in particular the required signal bandwidth, can be conflicting. Push–pull, in principle, can take on a different role in resolving this conflict.

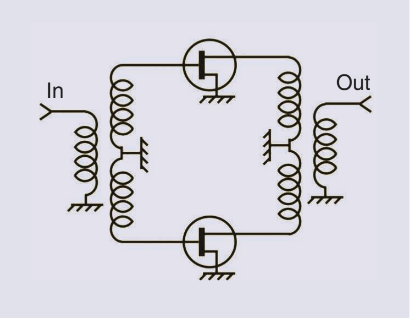

Figure 1. *A basic push–pull amplifier schematic.*

Figure 2, which I reproduce with some mixed feelings, shows the current and voltage waveforms for a classical class-B RF amplifier. The current, through the action of the transistor bias setting, is a half-wave rectified cosine wave; that's the easy bit. But time and again, in books, papers, and blackboards through the ages, the voltage is shown as a "zero-grazing" cosine wave. I hesitate to disclose my age when I was first puzzled by this; I probably first encountered it in some ham radio handbook from the 1950s. The heavily distorted current waveform is rich in harmonics, and the voltage can be (and often is) almost

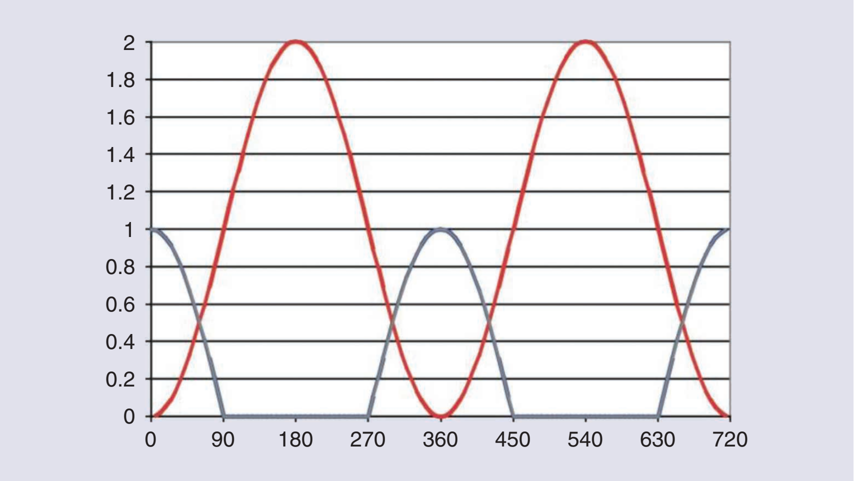

Figure 2. *Class-B waveforms; voltage (red) normalized to Vdc, and current normalized to peak value.*

anything, depending on the properties of the output load. Ideally, we would very much *like* the voltage to be the cosine wave as shown. This set of waveforms, if realized by whatever means, will deliver maximum power from the device at an efficiency of just over 78%. But, to achieve this, the fundamental load has to present a specific resistive value at the fundamental frequency and a short circuit at all harmonic frequencies. For low and even moderate bandwidths, quite simple circuit configurations can deliver an acceptable, albeit approximate, solution to these requirements. But there is clearly a conflict if the bandwidth extends beyond an octave; you can't have a network that provides a short circuit at the upper end of the octave band while simultaneously providing a resistive load when the signal moves to the same upper frequency.

In practice, when the active device is a transistor, the likelihood of achieving the perfection of Figure 2 is modest. Although acceptable power and efficiency are routinely obtained in solid-state RFPAs, the actual waveforms are more likely to fall into the general category of "continuous modes" [2], whereby the voltage retains a substantial second harmonic component. To be fair to the older texts, when the active device was a vacuum tube, the ideal waveforms would represent a more reasonable approximation, inasmuch as the output would consist of a very high-Q resonant circuit. This was mandated due to the very high loadline resistance of a typical tube; hundreds of volts at tens of milliamps imply an output load of many kΩ. Furthermore, the very sharp resonance could typically be "tamed" only by having some kind of mechanical tuning arrangement that enabled the exact resonant point to be maintained (older readers, like myself, may remember "dipping the plate"?).

In fact, it is in the challenge of shorting the second harmonic that the push–pull configuration has, in principle, a critical advantage. If the output combiner is indeed an ideal center-tapped transformer, the second harmonic output components in the two devices excite the primary windings in a symmetrical even mode and are thus canceled. But, for this to work, the transformer windings have to be very close to ideally coupled. As such, and indeed in just about every other frequency range, a push–pull transformer needs to use a core of suitable magnetic material to boost the coupling factor into acceptable territory. The problem is worth quantifying, and even the simplest representation in Figure 3, seen in any elementary circuit theory book as an introduction to mutual inductance, will suffice. The two main assumptions for ideal transformer action are infinite inductances L_1, L_2, and perfect coupling, so $M^2 = L_1L_2$ or $K = 1$. Rather than reproducing the equations, which gets surprisingly unpalatable, a more "RF perspective" can be seen by looking at the Smith chart in Figure 3(b) for a frequency range of 0.5–3 GHz. It turns out that the infinite inductance requirement can be substantially eased with the perfect coupling maintained, $L_1 = 10$ nH, $L_2 = 5$ nH; and the trace can be seen to hover quite close to the "ideal" resistive value of 25 Ω (how's that for a broadband matching technique, rather than all that Chebychev-filter stuff you microwave guys use, PIA would ask). But as K is reduced from unity, even very slightly, the trace veers off into oblivion to look more like a series inductance with the primary resistive termination barely showing itself.

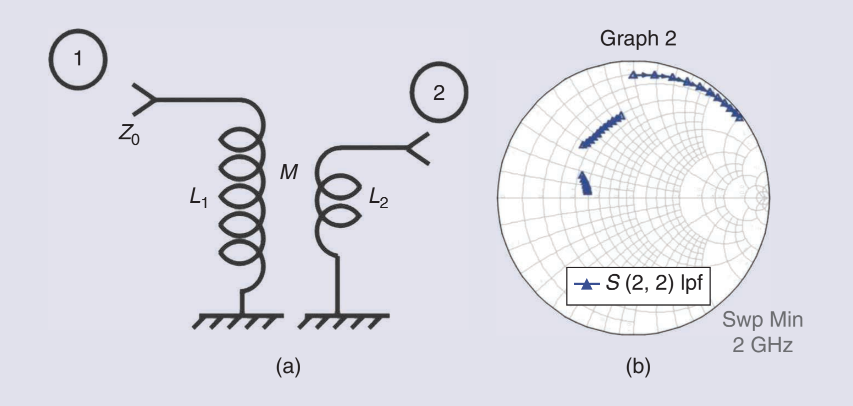

Figure 3. *Coupled inductors: the (a) schematic and (b) input impedance for varying coupling (K) factors. Values K = 1, 0.9, 0.5. Swp: sweep.*

There are some caveats here. At RF, the situation can be mitigated somewhat by using coupled resonators rather than coupled inductors. Then the required level of the coupling factor is strongly dependent on the Q factor of the resonators. In fact, consulting my own vintage reference on the subject [3], I note that for coupled resonators, the critical coupling coefficient is given by

$$K = \frac{1}{\sqrt{Q_p \cdot Q_s}}, \tag{1}$$

where Q_p, and Q_s are the respective Q factors of the primary and secondary resonators. Revisiting this formula after numerous decades, I suspect that herein may lie the reason that transformer matching may creep back into contention for low-power mm-wave CMOS RFICs, as indeed it did in the days of vacuum tubes. The two Q factors collaborate to reduce bandwidth but open a door to using coupled resonators where the inductors have coupling factors much less than unity. Not wishing to bang on about my misspent youth dipping plates, it is worth recalling that coupled resonators were a breeze in the high-Q environment of vacuum tubes; coupling to spare could be achieved, with air coils simply placed close, but not too close, to each other. But bandwidths were around 1%.

I will at this point resist the temptation to digress into a discussion on magnetic materials, which is a whole subject, and industry, in its own right, and, in all honesty, largely a complete mystery to me. My simple observation as a potential user would be that escalating losses become problematic as the gigahertz frequency range is approached, up to 1 GHz. It seems materials are available, and as such, PIA is quite correct; the "push–pull-transformer" approach is almost universal in the high-frequency and very-high-frequency (VHF) ranges, albeit relying on some very innovative and sometimes baffling transformer-winding strategies. PIA will no doubt refer me to a well-known vendor whose website shows transformer products up to several gigahertz, but these are restricted to low power levels, and losses become problematic for RFPA applications. There is a further problem, in that the plethora of measured data does not usually show even mode excitation and especially not at what would be the even higher second harmonic frequency band. With only odd-mode performance, the RF push–pull circuit degenerates into nothing more than a basic power combiner.

And so the microwave designer has to seek an alternative, and that lands us in the tangled web of baluns. Baluns can, essentially, replicate some of the functions of a transformer but use the properties of transmission lines. When I last looked, there were more than 500 U.S. patents on balun structures, so it is a well-trodden area. But there is a basic common denominator, which is shown in Figure 4. Essentially, if a transmission line is terminated at each end, the voltage between the inner conductor and the inside of the outer conductor has to remain constant. As such, the outer can be grounded at one end and "floated" at the other end; in this case, a split matched termination can be returned to ground potential at the midpoint, thus providing a differential signal, much as would be delivered by a center-tapped transformer.

The problem, and possibly the focus of a few hundred of the patents, is that there is a second transmission line formed between the outer conductor and "ground." Note that I now use quotation marks for the term "ground," as, all of a sudden, the microwave stalwart is a bit confused; he or she is not alone in this respect. Maxwell himself, perhaps in his modern reincarnation of an electromagnetic (EM) simulator, would have a few problems with this structure. There are two ground connections in Figure 4, each at the end of a transmission line that has a considerable physical length. The basic theory, as stated, is fine if these two points are indeed physically coincident, but, in practice, they are not; they are separated by this "ground plane" thing that we microwave folks consider, almost axiomatically, to be a zero-equipotential area. Thereby hang a fair few arguments I have had over the years, but fortunately, despite this concern, it does actually appear to work quite well. The "rogue" transmission line will limits the bandwidth due to forming a short circuited shunt stub (SCSS) when the balun line becomes a half-wavelength, but optimum performance can be obtained centered around the quarter-wave frequency point, and this bandwidth can be increased by devising methods of increasing the characteristic impedance of the rogue SCSS.

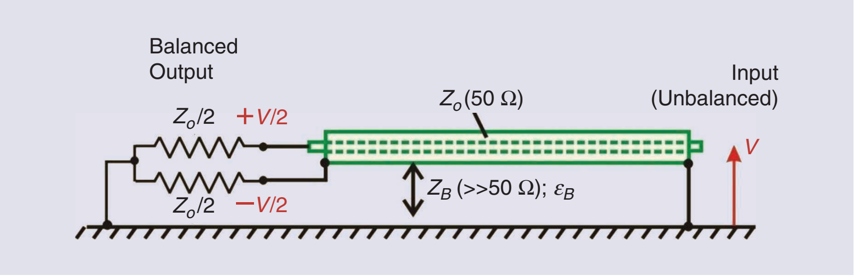

Figure 4. *A basic cable balun.*

But the "ground plane" assumption has always lingered in my mind. Over many years and many experiments, I have found that it can catch you out; some structures don't "sing." It seems there are folks who have managed to understand the deeper underlying theory, most notably Marchand, who not only has a famous balun named after him but wrote a seminal book [4] on EM theory that does appear to address these issues. (I obtained a dusty old copy via Amazon; it is well worth a read.)

The basic "cable balun" structure, notwithstanding the many variants, has certainly paid a lot of bills and is still widely used as a default option for push–pull amplifiers in the low gigahertz frequency range. But, once again, we have so far only considered it to be an odd-mode combiner (or splitter); what happens when we inject an even-mode second harmonic signal at the "business end"? In fact, this structure will present an *open circuit* to such an excitation: not quite what we wanted but at least on the right Smith chart circle. Once again, the "design space" of continuous modes allows useful designs to be achieved.

In conclusion, I feel I have spent a fair slice of my active technical life vacillating on this subject. Can we make push–pull work at gigahertz frequencies? *Yes*, but is it worth the extra effort? Well, I am not sure and might even say no. I have been involved in numerous exercises to design push–pull PAs at higher gigahertz frequencies and been reasonably happy with the results [5], but the hard fact is that when gallium nitride (GaN) technology came along, broader band designs could

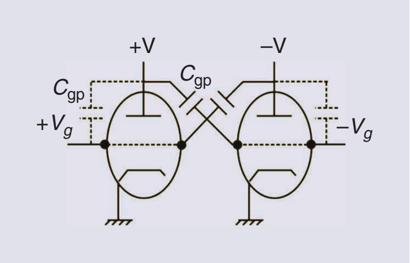

Figure 5. *A neutralization scheme for push–pull triodes.*

be implemented quite successfully using single-ended techniques. This is evident from the seemingly endless stream of articles in *IEEE Microwave and Wireless Components Letters* purporting to show incremental bandwidth and efficiency improvements using the admirable Wolfspeed 10-W GaN transistor. Old habits die hard.

I have a sting in the tail. Back in the days of RF vacuum tubes, stability and low gain were major problems. The main culprit for this was the very substantial capacitance from the grid to the anode (plate), which acted, as does gate to drain capacitance in our field-effect transistors, as detrimental feedback. But there was a range of techniques by which the feedback capacitance could be "neutralized," and by far the most effective of these was the use of cross-coupled capacitors in a push–pull circuit, as shown in Figure 5. By connecting a capacitor with a similar value to the internal feedback capacitor from the opposing anode to the grid, the feedback current could be canceled; in effect, this implemented a "negative capacitor" in shunt with the internal interelectrode capacitance. Some of the later high-power VHF double tetrodes actually incorporated these feedback capacitors inside the glass envelope (do a websearch on a QQV03-10 or QQV03-20) and represented quite a late revolution in VHF PA design, enabling the growth of vehicular radios, for example.

Given the headaches that "S_{12}" (as we now, in effect, call this problem) still cause for us in terms of stability and reduced gain, it has always been surprising to me that neutralization techniques have received little attention in the solid-state microwave era. Part of the reason, in fact, stems from the very fixation with single-ended techniques that PIA originally addressed. Although I have spotted these capacitors in some recently published CMOS RFIC designs, the potential offered by neutralization appears to have been largely ignored in mainstream microwave power device and circuit design.

I must, with some reluctance at this point, leave the story there for now, but watch this space.

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