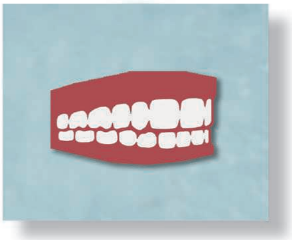

Vacuous Soundings

■ **Steve C. Cripps**

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Nostalgia, it would appear, is not what it used to be when it comes to electronics. Certainly, when it comes to publishing, my colleagues in the technical book business always gave me some very strange looks when I, or anyone else, had ventured to suggest writing a book on a "historical" subject. This is a bit surprising, given that the nostalgia thirst seems to run quite strongly in other engineering areas; vintage cars, for example, constitute a substantial economic sector both personal and commercial, along with a plethora of monthly glossy magazines. Here in the United Kingdom, there is an even more ambitious example, with the reopening of "heritage" railway lines, featuring (of course) steam locomotives driven by coal, which chug along for a few miles at 20 mi/h creating lots of smoke and dirt.

But that said, I can't say that a Fairchild uA702 op amp I found in an old cardboard box the other day aroused quite the same level of nostalgic interest, not to mention enterprise; in fact, what memories remain of my attempts to use this early entry into the op-amp arena mainly bring back memories of oscillations and mortalities. Generally speaking, I suppose electronic devices have not changed their external appearance all that much; an "old" TO-8 package looks much the same as a recent one, it's the performance that has changed. There is one kind of device, however, which is even older, which does still fascinate me, and this is maybe (dare I admit it) at least 55 years since I first encountered one. I am referring to the *microwave triode*, as I will term it, albeit not what it used to be called; in its heyday the term would have been *ultrahigh frequency (UHF) triode*, where the "ultra" initial referred to the then dizzy frequency heights of anything above 500 MHz. These devices probably had their aforementioned heyday in World War II radar development, although even they were largely eclipsed by newer vacuum developments in the form of the magnetron, and further into the 1950s the Klystron and Traveling Wave Tube

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(TWT) made their appearance, still to be seen in broadcast transmitters, not to mention most kitchens.

Taking care not to drift into an autobiographical monologue, I should maybe show the very first such device that caught my attention in my misspent teens (Figure 1). Known originally as the 2C39 (although I show its later evolution as the ceramic 3CX100A5) it actually had one of the longest survivals; even finding its way into some of the first 800 MHz cellular telephone base stations. Although running at recommended bias levels, it would have delivered somewhat less than 50 W in continuous-wave mode up to around 2 GHz, enterprising radio amateurs were able to extend this to 200 W using some enhanced water cooling techniques. These numbers may not sound remarkable in today's world of gallium nitride and laterally-diffused metal-oxide semiconductor technology, but back in the 1980s microwave semiconductor development was proceeding at a rather slow pace; the main impetus was military electronic countermeasures systems where replacing the limited lifetime of TWTs, especially those used on the receive side, attracted a modicum of funding, not to mention a few start-ups ☺. Gallium arsenide (GaAs) held the stage above 2 GHz, but anything much greater in power than a watt or two was getting exotic, and the devices were inevitably assemblages of multitudes of parallel connections of essentially small signal elements, running off a 6 V supply, and in truth maybe never admitted, did not show a whole lot longer lifetime expectancy than a vacuum device. Generating 100 W in the low GHz region was still the preserve of the vacuum triode, which could handle high voltage supply without batting an eyelid, and its convenient construction included an external plate connection that could be force-air cooled to handle dissipation in the order of at least 100 W.

Figure 1. *The 2C39 (3CX100A5) UHF triode (U.S. quarter and Euro for scale).*

Figure 2. *The 416B triode.*

So I have maintained something of a mini-museum containing a few of these interesting relics, without really putting much thought to ever again applying power to any of them. It turns out, however, that an unlikely reincarnation has been going on for some time and may even still be gathering momentum. A troll through eBay shows how substantial supplies of these triodes appear to be coming out of the woodwork, often in their original packing, and they are being snapped up at quite "healthy" prices. For example, Figure 2 shows a recent purchase of mine, a 416B triode that was developed in the 1950s for 3 GHz microwave links, and Figure 3 shows a 2C43 that was one of the more widely used devices and as a pulsed oscillator could generate up to 3 kW of power. There are also other devices of more recent origin becoming available from parts of the world who for various reasons were not quite so quick to reject the vacuum device, and that presumably have significantly improved performance.

It turns out that should I contemplate the construction of a vacuum triode microwave amplifier I would not have much competition. The folks who are purchasing these devices appear to be mainly the audio home-build fraternity, a subset of the "Tube Sound" audio faction that has been a growth area for a several of decades.

I will not venture too far into the subject of vacuum tube audio amplifiers, which appears to be a minefield well supplied by rivers flowing with snake oil. Although initially being dismissed by the mainstream electronics community, probably sometime back in the 1980s, it has grown into a substantial industry and one feels there must surely be some valid substance in its technical underpinnings. My perception, on a limited survey of the subject, is that the "tube sound" is favored more by musical performers than passive audiophile listeners. Indeed as a still-active performer myself, albeit in the classical idiom, I am only too aware that amateur musical groups do not always produce sounds that are best left well alone by electronics or performing venue acoustics. Here in the United Kingdom, amateur classical groups, which can extend to full symphony orchestras, often perform in local churches whose echoing acoustics can certainly "soften" the odd rough edges from the first violins. And so I think it may be for the smaller amateur performing groups in the "popular" idiom; maybe a small dose of even harmonic distortion is good medicine?

Perhaps it is time to have a brief technical indulgence into the vacuum triode, and abandon any further attempts to justify it. I find them fascinating, for better or for worse; such a revival as has happened in the audio world is simply never going to happen in the microwave one, notwithstanding the fact that in terms of raw power generation they may still hold a technical advantage, most notably in pulse modes, whereby perhaps hangs the aspect that has recently caught my attention. But I have always been a believer that a little time spent looking into "old ways" can be instructive, if only in an indirect sense. So let's take a closer look at the microwave triode.

I suppose one of the reasons these things still fascinate me is their simplicity of construction, and even the simplicity of the physics of their operation. Electrons are emitted from the surface of a suitably coated metal cathode, under the influence of heating filament (1,000 °C typically) and are accelerated toward the plate by a substantial electric field cause by a high voltage supply applied between cathode and plate. There is, in fairness, much physics behind electron emission in vacuo, but the basic action always seems to me somewhat more intuitive than the Fermi Dirac statistics and energy level diagrams used to explain semiconductor junctions. Anyway, the placement of a metal "grid" into the electron path can control the flow of current; again, this seems to me rather more intuitive than the concepts required to understand transistor base or gate action, albeit maybe less so in the case of a field-effect transistor (FET). But, really, that is just about the whole story; in particular a microwave triode really does have the simple planar construction as shown in Figure 3, which is a somewhat remarkable picture in a number of respects and shows the inside of a 2C43 triode at the level of the grid ring.

Figure 5 shows a set of I–V characteristics that I measured on the 416B, and immediately shows some obvious differences from a transistor. Most notably, the plate current shows a monotonic increase with the plate voltage Vp, almost more in the manner of a resistance; this characteristic moves along the Vp axis as the grid voltage Vg is varied. As such, we do not see any obvious signs of "saturation," which is almost universal in comparable transistor I–V plots. Indeed, I managed to extend the measurements well into the positive grid bias regime, where the current continued to increase to the point where I had to apply the plate supply voltage momentarily to prevent excessive heating. But even in this ultracrude, quasi-pulsed mode, I was able to extend the plate current to a level 10 times higher than the recommended continuous rating of 20 mA, and still maintain unchanged, or even slightly enhanced, transconductance. Even on this basic measurement, it appears that the current and voltage limitations of a vacuum tube are mainly a matter of handling the dissipated heat than any other physical saturation effects (and don't they look "straight"?!).

This is where I find, in my recent researches on the subject, that vacuum tubes hold a remarkable secret that seems to be rather glossed over, even in some of the seminal reference works on vacuum tubes [1]–[4] that still lurk in my personal library. It is said, almost as if an admission [4], that if the pulsed IV measurement concept is extended to a very short pulse of plate voltage, of the order of microseconds, the plate current can be increased with applied plate and grid voltages by possibly two orders of magnitude above its recommended continuous value; a device that would normally operate with a continuous current of 20 mA at 250 V plate voltage can pull a whopping 2 A at 2 KV plate voltage for a microsecond or so, providing that the pulse repetition rate is kept appropriately low. Whether this was simply a matter of maintaining the heat dissipation within the continuous rating, or (as is intimated) limitations in the actual emission process is not clear. Nevertheless, this opens up the possibility of generating kilowatt levels of RF power using a very simple, small device, so long as the pulse duty cycle is kept low enough. For example, the 2C43 (possibly also designated a 464A), shown in its undamaged form in Figure 4, is one of the more well-known, and once widely deployed, devices in early radar systems, has a dual personality as reflected in an old data sheet: (see Table 1).

So this device was used both as a small signal RF amplifier, which is how I first encountered it (and actually used it, for the 430 MHz amateur band), but also as a radar transmitter generating upwards multiple kilowatts

Figure 3. *An internal view of a 2C43 triode at the grid ring level.*

of pulsed power, albeit using pulses of a microsecond at duty cycles no more than 1%. In this latter mode, the device would be employed as a self-excited oscillator, and was used as such at frequencies up to 3 GHz. It would be interesting, and maybe one to add to my techno-bucket list, to perform a pulsed I–V measurement of such a device; obviously finding a suitable high voltage pulse generator would pose a challenge now, as indeed it did at the time, and this may explain the curious lack of published information on this effect. Meanwhile, I cannot help speculating on the difficulties of implementing the same microwave performance using solid-state devices; transistors do not have the handy pulsed "boost mode" of I_{dss} and to generate 1 Kw of pulsed power one has to use a device capable of generating almost the same level power in continuous operation. To achieve the feat a single, small, modest, vacuum triode would still appear to be a better option, although such a requirement has largely disappeared from modern microwave systems, a "solution without a problem," perhaps. (Is this a case of a "fatal attraction" I have to such devices and nonexistent applications? See my "Microwave Bytes" column on avalanche diode oscillators [5].)

Figure 4. *A 2C43 triode capable of generating 3 kW of pulsed power at 3 GHz.*

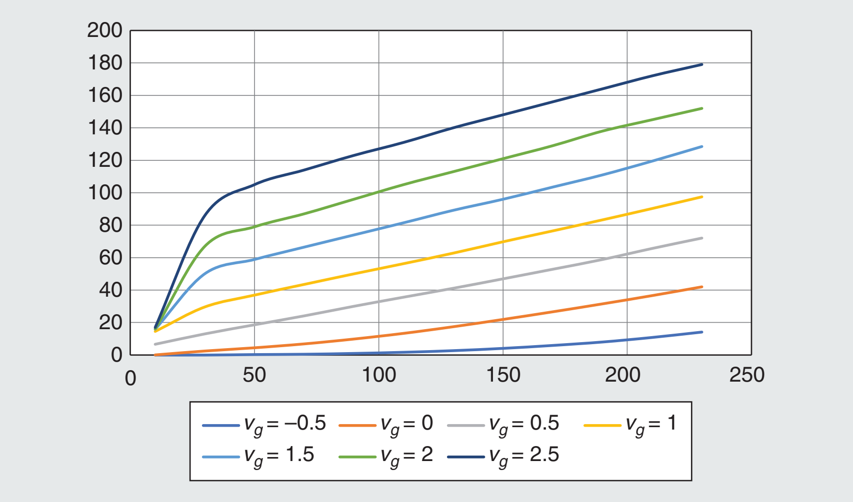

Figure 5. *The measured I-V characteristics of a 416B triode.*

Returning to the continuous I–V characteristics, it is equally straightforward to establish a reasonable circuit model for such a device, as shown in Figure 5. The I–V characteristics can be captured as a dependent voltage source with a series resistance, and the two main capacitances are from grid to cathode and cathode to plate. Here lies the fundamental problem with using such devices at higher frequencies; the grid to plate capacitance, C_{gp}, will almost always be high enough to cause serious stability problems. This was especially so in microwave triodes where the plate to grid spacing is made as small as technologically possible to increase the transconductance and maintain useful gain at higher frequencies where the inter electrode capacitances take their toll. (The old "gm/Cgs" still seems to apply as a gain criterion!) For this reason, microwave triodes were almost always operated in common grid mode, which reduces the available gain but largely eliminates instability due to the very small residual capacitance from anode to cathode. I note with some nostalgia of once thinking we should use our GaAs FETs in common gate to improve stability; sadly in a FET the source to drain capacitance is substantial due to the close proximity of source and drain metallization.

TABLE 1. 2C43 characteristics.

	2C43 Continuous Mode	2C43 Pulse Mode (3 GHz Oscillator)
DC Plate Voltage	500 V	3500 V
DC Plate Current	40 mA	2.75 A
Plate Dissipation	12 W	

The upside of common grid operation is that the input impedance is approximately 1/gm, so that for transconductance values in the 10–50 mA/V range this results in a potentially compatible impedance in a 50-Ω system, although the 50-Ω standard was less well established in these older times. But the interesting challenge is the output match. The resistance represented by a 20 mA device running at 250 V is several thousand ohms. Not only is this an enormous transformation from a 50-Ω load, but the output capacitance of 1–2 pF will swamp the resistive component at GHz frequencies. This puts an immediate constraint on the quality factor (Q-factor) required from the passive matching network, and is a good deal higher than what we obtain from today's open microstrip structures. But given a computer circuit simulator, not to mention a vector network analyzer (VNA), both very modern luxuries in the eyes of a 1950s microwave designer, it is tempting, and as a minimum entertaining, to take a look at a typical triode using these modern tools. My focus at this point is the 416B, shown in Figure 2, mainly because this was used in 3 GHz microwave links and has some extensive information available on its design, construction, and performance [6], [7]. In particular, [7] describes in some detail the circuit design that yielded over 10 dB gain at 4 GHz.

Actual measurements using a VNA would involve a certain degree of preparation, not to mention metalworking, but the simulation is easy enough. Indeed, using parameter values given in the references (gm = 50 mA/V, μ = 300), Microwave Office gives the *S*21 plot shown in Figure 7 (would this be perhaps the first time such a device has ever been simulated on a PC-based commercial simulator?). I have to say, the result rather resembles the first 1-W GaAs FET that I measured, with some dismay, back in the mid-1980s. Confronted with a device that has a shortfall of over 6 dB in its 50-Ω gain, I usually feel some amount of doubt about my matching skills, and so it is again here.

Browsing the old textbooks in my possession, it seems that the default solution to matching the desperately high output impedance was a 3D structure, shown in the cross section in Figure 8. Basically a closed cylindrical metal box is placed between plate and grid, thus forming a symmetrical inductive path to the grid ground plane. In fact, this can be viewed more analytically as a radial cavity, loaded across the center of its faces by the tube C_{gp}. The output is extracted using a small coupling loop near the periphery of the resonator, which couples into the radial magnetic field and will implement a suitably high impedance transformation ratio if designed appropriately.

When contemplating how one could, on an a priori basis, design such a configuration, I am reminded of Kipling's famous "Road to Mandalay" poem (not the much later Sinatra song!), the bit about "there ain't no busses runnin'

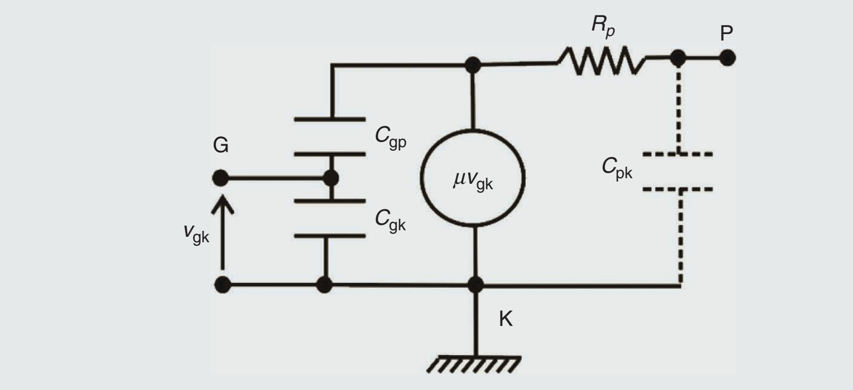

Figure 6. *A small signal model for UHF triode.*

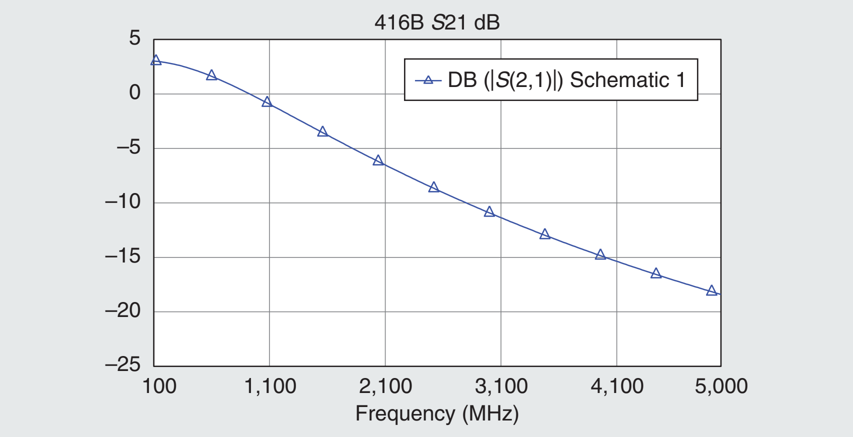

Figure 7. *Simulation of 416B unmatched gain in 50-Ω system.*

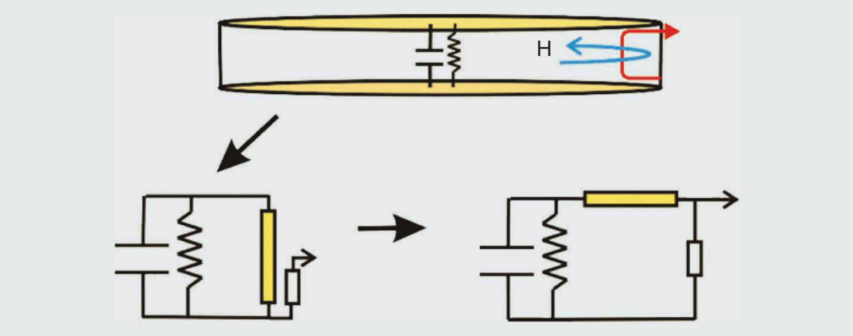

Figure 8. *A radial cavity output match; evolution to an equivalent circuit shown here.*

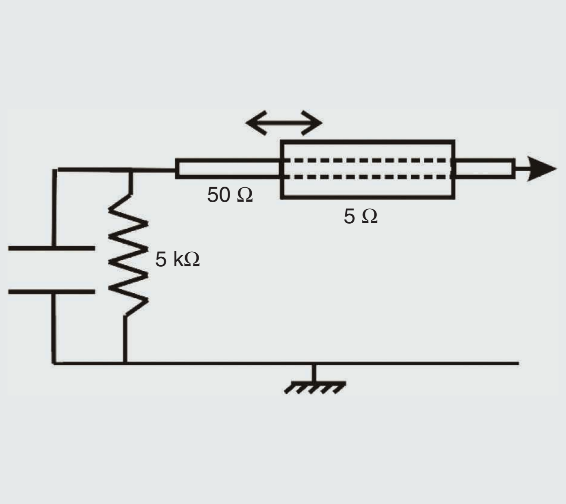

Figure 9. *A possible alternative output match.*

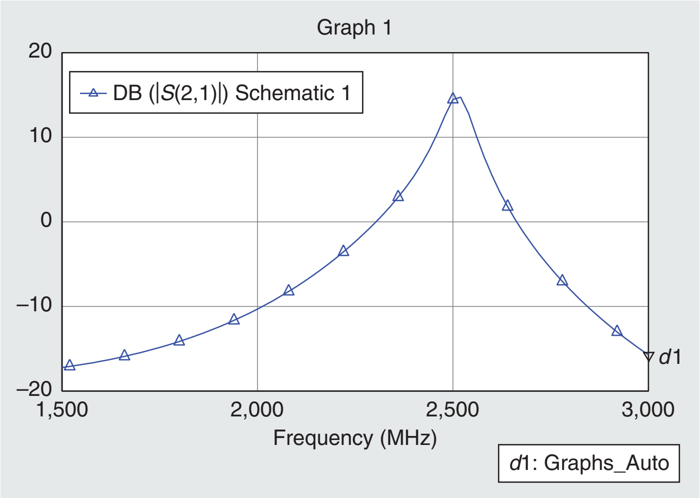

Figure 10. *A gain simulation for matched 416B amplifier.*

from Bank to Mandalay"; no modern circuit simulator to my knowledge has such a model in its library(!). However, and as noted at some length in a recent "Microwave Bytes" column [8], there would appear to be two different ways of viewing this problem, perhaps once again showing the cultural differences between engineering and physics cultures. Taking the "physics" view, one can, through the field equations, establish the resonant magnetic field and thus determine the induced voltage in a coupling loop of known area, although this would assume the self-inductance of the loop is negligible. I rather think the more pragmatic "engineering" approach would be to go through the transformation sequence also shown in Figure 8. The radial cavity behaves, in effect, as a short-circuited shunt stub (SCSS), and at resonance the magnetic field will have a maximum near to the short circuit position, where the coupling loop is placed. Within the closed confines of the cavity, it appears we are allowed to assume that the loop snags almost the same magnetic flux as the cavity walls, and so the next step is to approximate the coupling loop to a tap near to the end of the SCSS. A bit of a handwave, perhaps, but we do now have a matching network that can be analyzed using a standard circuit simulator and starts to look more familiar to today's RF designers.

In fairness, I should mention that in the precomputer era much admirable effort was expended in deriving analytical formulas for designing such structures, and can be found in some of the quoted references. As such, even in older times, the final design was not entirely a result of cut-and-try techniques, but they must surely have played a part. Some things don't change.

In fact, using my more "modern" perspective, I rather think I would try something different, and try the more well-defined configuration shown in Figure 9. The output capacitance is resonated out using a 50-Ω transmission line, which simultaneously inverts the high resistive component to a correspondingly low value. For example, to match up to 5 kΩ, a quarter-wave 50-Ω line will result in a slightly less scary 0.5 Ω to match up to 50 Ω. A simple mental calculation tells me this would require a $\lambda/4$ transformer having a 5 Ω characteristic impedance, which although problematic in the planar microstrip world is not by any means outrageous in coaxial airlines having the quite large radii defined by the tube dimensions. I would wager that the relatively large dimensions, along with some judicious silver plating, would make the necessary mark in terms of Q-factor. Such a structure would also lend itself to mechanical tuning, as indicated.

The simulated result for the 416B is shown in Figure 10. Obviously the frequency response is narrow, due to the Q-factors involved. Herein perhaps lies another nail in the microwave triode coffin, already well closed. And we have not even mentioned operating lifetime. But maybe fun to try? Thinking about it . . . going back to the audio tube revolution it does occur to me that measuring the intermediate modulation performance may raise a few eyebrows.

Whether anything can truly be learned from this little excursion into microwave history is very much a matter of personal judgment. Nostalgia in electronics may not be what it used to be, but it makes a change, and certainly provides food for thought.

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