Microwave Bytes

VNA Tales

■ Steve C. Cripps

Being loosely coupled to the technical publishing business these days, I have been amused by the reactions of my editorial colleagues when they hear the word "history." They start emitting strange hissing noises and make explicit antivampiral gestures. I am assured that any attempt in print to venture down memory lane will always go down like a large lead balloon with the technical readership. Nostalgia, it seems, is not what it used to be in engineering circles, and in many ways I agree. There's nothing worse than listening to a bunch of old codgers spouting on about tubes, Lecher lines, and log tables.

That said, I feel that occasionally it does pay to revisit the technical archives. I enjoy the occasional trip to my garage to look up old papers in my still-intact library of *MTT Transactions* (which, in my case, goes back to 1981). Yes, I know it's now all on CD, which of course I also have. But I'm reluctant to dispose of my *MTT Transactions* library. Time and again, I find that when I triumphantly pull out the single issue containing the target paper, I scan the contents and find a couple of other papers that look really interesting and worth a read. Indeed, I think it is one of the great aspects of our transactions that so many of the papers were ahead of their time and become part of mainstream practice as much as a decade later. So, for a lesser mortal like myself, I actually find I understand more—and get more from—older papers that are nevertheless relevant to what I am trying to do today. Reinvention is still alive and well.

So from time to time, I have decided that I will open Pandora's Box and get a bit historical. For example, sometimes there is something that once was all the rage, but seems to have fallen by the wayside. Such topics are not only possible candidates for reinvention, or reincarnation, with the realization that 10 or 20 years of progress in RF technology might make them relevant again, but perhaps they also highlight how wrong we can be about where we spend our R&D bucks. A particular technical area may be getting a lot of attention right now, but in ten years' time it could be all but forgotten, the dozens and hundreds of papers archived in garages. My first topic under this heading is the vector network analyzer, or VNA, as it has now become known, to distinguish it from its lowly scalar relation. Not that the VNA in its modern form has fallen by the wayside—far from it. But the history of this subject is of some interest, and it also has a noteworthy skeleton in its closet—the ill-fated six-port reflectometer (6PR).

The VNA theme has been stimulated by some recent commentary in *IEEE Microwave Magazine* on the 8410, the first definitive microwave network analyzer

Steve C. Cripps is with Hywave Associates, The Mangold House, Hare Lane, Buckland St. Mary, Chard TA20 3JS Somerset, U.K., stevehywave@aol.com.

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from the then Hewlett Packard (HP) Company. As my friend and former colleague John Eisenberg wrote in the

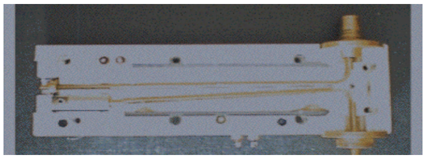

Figure 1. *Directional coupler from HP8742A reflection test set.*

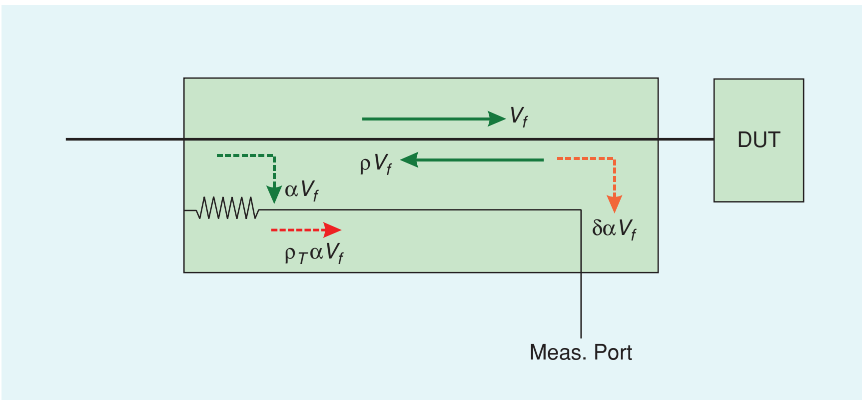

Figure 2. *Directional coupler "imperfections."*

February issue, I also marvel at the breadth and depth of superlative engineering that went into this seminal product. The photos in his article [1] show one of the mechanical line stretchers, which to this day remains (as far as I know) the best adjustable precision 50-Ω line ever made. I actually still use a pair of them in a test setup, not just because they can be obtained cheaply on eBay, but because there is simply nothing in their performance class on the market. They have a return loss better than 20 dB up to 18 GHz, a length adjustment of 15 cm, a precision mechanical readout with 0.1 mm resolution, and a loss measured in tenths of a dB. The broadband couplers, which formed part of the same transmission and reflection test boxes, were also remarkable given that their tapered designs predated the availability of electromagnetic simulators by about four decades. (Figure 1 shows a partially dismantled example.) I love the way the coupled lines are turned through a right angle; the center conductor is shaved thinner, and a little curvilinear triangular piece of aluminium maintains the immaculate return loss while also defining the end of the coupled section (right center of Figure 1). I trust, and indeed hope, that getting this bit right involved files of the mechanical, rather than a digital, variety! I have to admit that in taking apart some of these monuments to traditional microwave engineering excellence to recover the useful components, I feel a twinge of guilt that I am engaging in an activity that is tantamount to desecration. But at least the precision coaxial switches, couplers, attenuators, and connectors all find ongoing use, their gold plating still shiny after 30 or 40 years.

The 8410 was an instrumentation breakthrough in that it could measure both magnitude and phase of the reflection and transmission parameters of a microwave network. This was clearly seen as an important requirement by the market strategists at HP in the early 1960s, and given the vast array of custom-designed components that had to be designed to make a marketable product, one must acknowledge the savvy of those who assigned the development funding.

The 8410 system used directional couplers to separate out the forward and reflected waves on a transmission line, which was terminated with the device under test (DUT). The amplitude and phase measurements were done at an intermediate frequency (IF), and the downconversion process used a sampling technique. The Grove sampler, which forms the heart of the 8411 harmonic downconverter, is a technical icon in its own right [2]. I have sometimes wondered whether this intriguing device was originally developed to make a sampling oscilloscope or whether it was initiated as a sampling downconverter for the 8410. I also wonder about how much discussion there was about alternative methods for achieving the same measurement goals. The classical solution for measuring microwave impedance was, of course, the slotted line. This wonderful gadget (sorry!) also reached a classically well-engineered zenith in commercial versions manufactured by HP and General Radio, sadly relegated these days to ornamental use on the capacious office shelves of corporate research fellows. They were, of course, very much manual devices whose operation required such human intervention as location of minima as a wheel is slowly turned. This does not seem like a promising start for an automated measurement, which sweeps frequency over a broad, multi-octave range. HP had already demonstrated the use of sampling techniques for microwave phase measurement with the 8405 vector voltmeter, and clearly headed further down this path in the 8410 conception.

Yet, there always was an interesting alternative for making microwave vector measurements, which became known as the 6PR. The key feature of this technique was the ability to measure phase using only amplitude sensing, with the resulting huge potential benefit of eliminating the need for downconversion, with its complex overheads in specialized downconversion components and IF measurement circuitry. What the 6PR did need, though, was “on-the-fly” computation, which back in the early 1960s was a no-go area. It is indeed

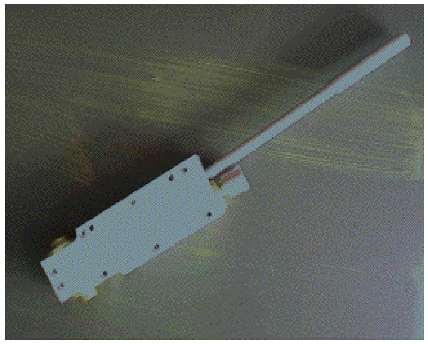

Figure 3. *Coupler (from 8746 s-parameter test set) with external lossy line termination.*

interesting to speculate that the reason HP chose to go down the sampling downconverter path was fundamentally based on the need to display the swept frequency measurements in "real analog time;" any signal processing had to be done using on-the-fly analog techniques. There seems little doubt that the 6PR generated plenty of interest and funding in the 1960s and 1970s, and survived a good deal longer that that. To my knowledge, commercial products were developed by at least two instrument companies. I also know there were some others that never made it to the marketplace, but meanwhile soaked up plenty of development funds. The transactions of the first MTT symposium I attended—San Diego in 1978—has a whole session devoted to the subject, and this was undoubtedly the case for a few more years before and after that event.

It is interesting still to compare the two approaches, even though the 8410—especially with its more recent 8510 derivative—ended up surviving and outstaying all attempts to usurp it by the six-port community. In the predigital era, one important fundamental problem in the use of couplers to separate out the forward and reflected waves from the test device was directivity. The quantitative implications of finite coupler directivity are worth briefly recalling. As indicated in Figure 2, a forward wave having a complex amplitude V_f reflects from the DUT to create a reflected wave which couples into the output measurement port and has a complex amplitude

$$V_m = \alpha\rho V_f,$$

where ρ is the complex reflection coefficient of the DUT and α is the coupling factor. The contaminating signal from the imperfect coupler directivity is added to this measured voltage, which then becomes

$$V_m = \alpha V_f(\rho + \delta), \qquad (1)$$

where δ is the inverse of the directivity ratio, normally expressed in dB relative to the output at the coupled port. So, δ effectively adds itself, vectorially, on to the intended measurement target of ρ.

At any given frequency, the various necessary lengths of transmission line plumbing in the instrument contrive to make the phasing of the two voltages essentially random. As the frequency is swept, the phasing between the two terms will spin around the phase plane at a considerable rate of knots, giving a telltale ripple on the measured port output amplitude. This ripple will show a phase change as the reflection at the test port changes, for example, neatly

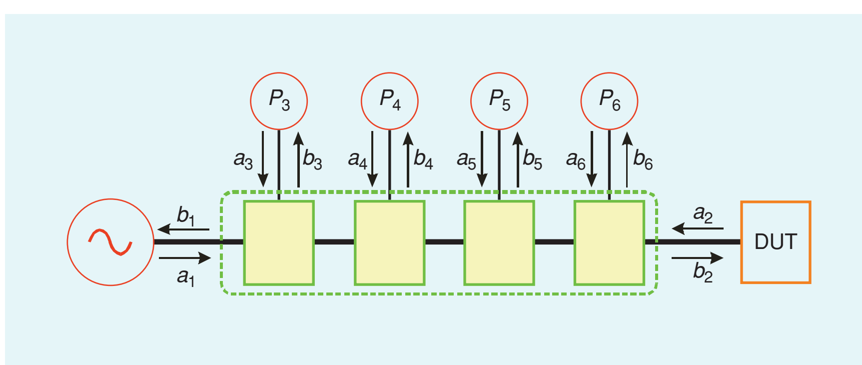

Figure 4. *The 6PR.*

inverting as a short-circuit termination is replaced by an open. This basically tells us that when it comes to correction techniques, calibrating the system using a simple short-circuit reference subtraction simply won't do. Unfortunately, this VNA calibration shortcut is still covertly used by many who should know better (yours truly included!).

With 30-dB directivity, δ is just over 3%, and the resulting measurement may be useful enough for many applications. At 20-dB directivity, the voltage error signal is up to 10%, which all but derails the measurement for most practical purposes. At high reflection magnitudes, a 3% error may not necessarily be excessively troublesome. But when measuring low reflections, the rogue signal severely restricts the dynamic range of the measurement. There are many other sources of error in the system, but this quantification gives a clue that with no other corrections being applied, the couplers will require a minimum directivity of 30 dB for the raw measured data to even be presentable. Clearly, the design and fabrication of the highest-directivity couplers was a major element in the development of the 8410. Examination of a typical coupler (Figure 1) shows the use of a tapered coupling section and a precision internal load. As any coupler manufacturer knows, there is little point in implementing a high-directivity coupling structure unless the isolated port is supremely well terminated. This can again be quantified using Figure 2; if the forward voltage is, as before, V_f, then any reflection from the isolated port termination will send another contaminating signal to the measurement port, having an amplitude of $\rho_t \alpha V_f$, where ρ_t is the reflection coefficient of the isolated port termination. Referring back to (1), the measurement port voltage is now (approximately, ignoring the coupler transmission factors)

$$V_m = \alpha V_f(\rho + \delta + \rho_t),$$

which indicates that the termination reflection coefficient corrupts the measurement in similar fashion to the directivity and may in practice be difficult to distinguish from the directivity error. Clearly, the termination needs to have a return loss which has a substantially lower dB value than the directivity in order to exploit the value of a high-directivity structure. So we make a coupler with 30-dB directivity, and we thus must make the termination much better than that, maybe approaching 40 dB return loss.

In a VNA, this means—in the first place—that separate couplers have to be used for sampling the forward and reflected signals, but even then special attention needs to be given to the terminations on the isolated ports. Some of the test boxes for the 8410 implemented these loads using lossy transmission lines, which projected most awkwardly out of the coupler body as shown in Figure 3. Maybe there was an additional advantage in this approach of being dc open circuit, although I have to speculate that the originator of this fine contraption must have had to do some fancy footwork in design review meetings!

Despite the excellence and precision of the engineering, it quickly became apparent that the performance of the 8410 could be greatly improved by the use of online data processing. It was, perhaps, fortunate that smaller computers capable of performing this task started to become available around the same time. This enabled a more rigorous approach to the removal of the many sources of measurement errors. Given a friendly online computer, the errors could be consolidated into a conceptual "error matrix," whereby the raw measured T-parameters are transformed into the actual device parameters

$$[T_{\text{Meas}}] = [T_{\text{ErrIp}}][T_{\text{Dev}}][T_{\text{ErrOp}}],$$

where $[T_{\text{Dev}}]$ represents the actual device parameters and the $[T_{\text{Err}}]$ matrices represent the measurement errors on input and output.

I must say, when I first encountered this formulation, I was more than a little suspicious. Who says such a complex, multidimensional problem can be stated in such simplistic terms? Well, it seems no one else complained, and it certainly appears justifiable, based on the reciprocal and linear behavior of

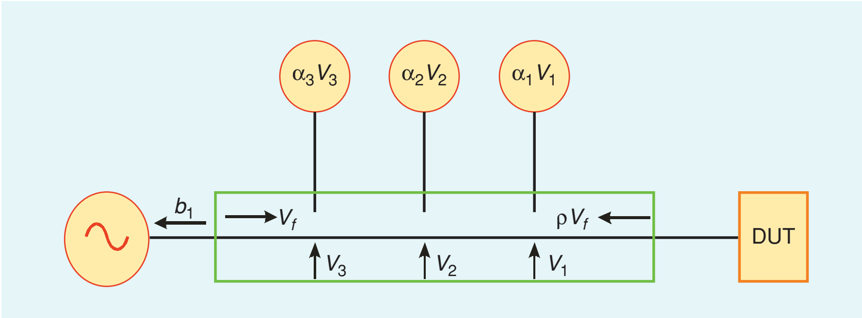

Figure 5. *Simplified five-port measurement of DUT reflection coefficient.*

passive linear networks. It is actually a very interesting case of how behavioral modeling can sometimes blow physical modeling out of the water in solving practical problems more efficiently. By selecting various different standard and/or "known" elements for T_{Dev}, it becomes an apparently more straightforward and systematic process to determine the elements in the error matrices and hence eliminate the systematic errors.

Would life be so simple! Elegant though this formulation may be, it only corrects the errors within a well-defined environment of high-precision coaxial connectors and standards. In interfacing this now pristine, error-free instrument to our comparatively Heath-Robinson microstrip test fixtures, we muddy the waters again, and in a manner that too often is never fully reversed. Yes, I do know something about TRL (thru-reflect-line) fixture calibration. But despite the theoretical assertions to the contrary, I have always found the "deembedding" process a fiendishly difficult one to implement properly. All too frequently, in my observations, VNA measurement accuracy falls well short of the capabilities of the instrument itself, which somehow seems to lurk inscrutably behind its pristine coaxial interface. In my mind, over the years, this has raised the question of whether the expenditure on such instrumentation horsepower is truly justified in the first place.

The concept of measuring the phase of a microwave signal without performing a literal phase measurement seems a contradiction in terms, yet this is precisely what the 6PR can do. Based on the entirely reasonable assumption that accurate, high-dynamic-range power measurement is readily available, the 6PR protagonists sharpened their pencils and came up with some basic theorems on how phase can be measured with only power sensors [3], [4]. A key feature of the 6PR, as extensively researched in the 1970s and 1980s, was the stipulation that the measurement network would be characterized as a full six-port network. This removed errors that creep in when sampling probes are poked into transmission lines, with the hope that they do not significantly affect the measurement. In practice, the six-port network was usually cobbled together using various couplers and power splitters. But as indicated in Figure 4, a measurement "surface" could be defined that had six ports coming out of it, with no particular internal plumbing configuration being defined.

The full six-port scattering matrix states that the output wave from each of the six ports is a linear function of the input wave on all of the five remaining ports

$$\begin{aligned} b_1 &= s_{11}a_1 + s_{12}a_2 + s_{13}a_3 + s_{14}a_4 \\ &\quad + s_{15}a_5 + s_{16}a_6 \\ b_2 &= s_{21}a_1 + s_{22}a_2 + s_{23}a_3 + s_{24}a_4 \\ &\quad + s_{25}a_5 + s_{26}a_6 \\ &\quad \text{(etc.)} \\ b_6 &= s_{61}a_1 + s_{62}a_2 + s_{63}a_3 + s_{64}a_4 \\ &\quad + s_{65}a_5 + s_{66}a_6 \,. \end{aligned} \tag{2}$$

This generates an awful lot of *s*-parameters, more perhaps than most folks will ever have seen at one time. These are, however, all properties of the physical network, whose values can, in principle, be determined by a suitable calibration procedure at each frequency. The goal for the measurement, we should now recall, is to determine the ratio of a_2 to b_2 for the DUT port. This means we have to eliminate 10 out of the 12 unknowns a_n, b_n in (2), which thus requires four more relationships (noting that the 12 unknowns can immediately be reduced to 11 by normalization to one of the a_n, b_n variables). Hence, the stipulation of four power measurements, which give additional equations having the form

$$P_n = |b_n|^2 - |a_n|^2 \quad (n = 3, 4, 5, 6)\,. \tag{3}$$

Given that the a_n, b_n voltage waves are represented here as complex amplitudes, it is not immediately apparent that (2) and (3) are actually sufficient to reach a unique solution. It is appropriate here to note the very elegant work of Engen and Hoer [3], [4], whose transformation of these equations into graphical form clearly shows this must be the case.

In some respects, the 6PR could be considered a derivative of the slotted line, but rather than having a single movable probe, four fixed probes are placed at suitable intervals along the test line. But added rigor and accuracy are introduced by allowing for both voltage and current sensitivity for the probes and also by including reflections from the probing elements back into the main test line. This generalized formulation now has to be explored in order to come up with viable physical implementations. A "FAQs" list might read as follows:

- Are four power measurements just a minimum, or would more measurements be better?
- Do we try to simplify the six-port characterization by designing special coupling structures? Can't we assume the power meters are well matched and the a_{3-6} terms are close enough to zero to be ignored?
- Isn't there a potential problem when the spacing of the sample points approaches a half-wavelength, and isn't this going to be a problem in broadband swept measurements?
- Rather than having one coupler to correct (as in the conventional VNA), don't we now have four? Isn't this really going to be a bit of a calibration nightmare?

One could be ungracious and suggest that the above list of FAQs largely defines the demise of the six-port technique. In the first place, the 6PR community had to compete with an existing instrument that with computer correction and calibration could achieve impressive precision and dynamic range. The 6PR was not to be compromised as a "cheap-and-cheerful" alternative. I think this was the opportunity they missed, since if some shortcuts are allowed, it may well have been possible to market a low-cost instrument that could still be useful for many applications. As I mentioned earlier, I often get the feeling that an 8510 or 8720 does "too much," certainly more than what I really need to use it for. They seem to be instruments more designed for use in a standards lab rather than the more prosaic environment of an RF engineering development lab. My experience, in many RF labs all over the world, is that the aforementioned problem of physically extending the capabilities of a fully calibrated VNA to devices mounted on external test fixtures frequently devalues the benefits of full calibration. I find evidence to support this by observing the thickness of the dust deposit on the finely crafted hardwood boxes in which the expensive calibration kits are usually sold!

The 6PR was the subject of many papers throughout the 1970s and 1980s (I got nearly 400 hits on IEEE *Xplore*). The relatively simple mathematical formulation conceals a multitude of issues, such as the selection of an optimum physical configuration, calibration, and quantification of the impact of measurement errors. There were one or two commercial instruments released, but they did not seem to survive for very long, the most notable perhaps being one made in the United Kingdom by Marconi Instruments. By all accounts [5], this was an excellent instrument, but the domination of the microwave instrumentation field by HP unfortunately made all of these products nonstarters commercially, underlined by the timely appearance of the much-improved 8510. But I also feel that the precision engineering legacy of the 8410, which was largely preserved in the 8510, still paid off even in the modern era of digital correction. The concept that digital correction magically transforms any old junky piece of hardware into a precision item has become the flavor of the times in our field. I do, however, still like thinking that it's worthwhile to get somewhere close to the right answer before engaging the power of digital correction. But I suppose upon reading this some readers will think I'm about to drift into tubes and Lecher lines.

Back at my own ranch, I still have a need to measure microwave impedances and I can't afford a VNA. It's a problem that has bugged me for a long time. I'm not looking for pristine accuracy. Even knowing which quadrant of the Smith chart I'm in would be of some use, and something just a bit better than that would do the job. For example, when doing load-pull tuning, it would be nice indeed to have instantaneous readout of where I am on the Smith chart as I tune. Of course, I can spend dizzying amounts of money and buy a computer-controlled tuner system. But, without in any way criticizing such products and the folks involved in selling them, there are many like me who simply can't justify the capital expenditure based on the limited usage. Most commercial systems, in any case, use an a priori calibration database to specify the impedance at any given setting.

It turns out that a much simpler system can be proposed (see Figure 5) that streamlines the generalized 6PR but can still fulfil this function to an acceptable level of measurement accuracy for many applications. Figure 5 shows a simple probing structure for a transmission line, which can be considered to be a more direct descendent of a slotted line but with fixed measurement points. It is a matter of simple logic that a probe that is placed symmetrically with respect to the length of transmission line structure will show no directional properties; the output voltage will be the same regardless of which end of the line is excited. Such a structure will, thus, in principle only respond to voltage and not to current, although its frequency response and coupling factor α will be dependent on the more detailed design of the probe. I was intrigued to discover that if indeed we can probe voltages in this manner, the forward and reflected waves on the line can be uniquely determined by a system using just three voltage probes measuring only power. Although at first this may seem in conflict with the four-sample requirement stipulated by generalized six-port theory, it turns out that we have made some shortcuts. We assume, for example, that the probe coupling factors are sufficiently small that the forward and reflected wave amplitudes remain constant throughout the main line.

If the probes, through their calibrated coupling factors α_n, are able to indicate the voltage magnitude on the line at three positions, V_1, V_2, V_3, and the phase reference is taken at the V_1 probe location, we can write

$$\left|\frac{V_1}{V_f}\right|^2 = 1+\rho^2+2\rho\cos\theta$$
$$\left|\frac{V_2}{V_f}\right|^2 = 1+\rho^2+2\rho(\cos\theta\cos 2\phi_2 - \sin\theta\sin 2\phi_2)$$
$$\left|\frac{V_3}{V_f}\right|^2 = 1+\rho^2+2\rho(\cos\theta\cos 2\phi_3 - \sin\theta\sin 2\phi_3),$$

where ϕ_2, ϕ_3 represent the positions of the V_2 and V_3 probes relative to the V_1 probe, ρ and θ are the magnitude and phase of the DUT reflection coefficient, and V_f is the magnitude of the forward (incident) wave.

While they do have a distinctly unfriendly look about them, it is actually possible to solve these equations uniquely for ρ and θ, based only on scalar power measurements at the probes. For the record, see the equation at the bottom of the page.

Although V_f and ρ are still unknowns at this point, they are known to be positive real numbers, which is sufficient information to obtain a unique value for tan θ. The reflection magnitude ρ then becomes one root of the quadratic

$$\cos\theta = \left(\frac{1}{2\rho V_f^2}\right)\left(\frac{\left(V_1^2-V_2^2\right)\sin 2\phi_3-\left(V_1^2-V_3^2\right)\sin 2\phi_2}{(1-\cos 2\phi_2)\sin 2\phi_3-(1-\cos 2\phi_3)\sin 2\phi_2}\right)$$
$$\sin\theta = \left(\frac{1}{2\rho V_f^2}\right)\left(\frac{\left(V_1^2-V_2^2\right)(1-\cos 2\phi_3)-\left(V_1^2-V_3^2\right)(1-\cos 2\phi_2)}{(1-\cos 2\phi_3)\sin 2\phi_2-(1-\cos 2\phi_2)\sin 2\phi_3}\right).$$

$$\left(\left(\frac{V_2^2}{V_1^2}\right)-1\right)\rho^2+ 2\left(\left(\frac{V_2^2}{V_1^2}\right)\cos\theta-\cos\theta\cos 2\phi_2+ \sin\theta\sin 2\phi_2\right)\rho+ \left(\left(\frac{V_2^2}{V_1^2}\right)-1\right)=0,$$

which, as far as I can tell, always obligingly delivers just a single acceptable root, given that ρ is positive and less than unity.

I should say that I am not the first to recognize this method of measuring complex impedances. Hu [6] proposed it as the basis for a VNA system, and recently Qiao et al. [7] demonstrated a topical application in monitoring the impedance of a mobile phone antenna. The three probes can have spacings of 45° and 90° if only a narrow frequency band is of interest. This allows for a short measurement structure that will barely intrude on the tuning process.

I am not suggesting that this complex impedance monitor will cause the current VNA manufacturing industry to lose any sleep. I am really just promoting the concept that simplified versions of the 6PR may be worth revisiting in certain specialized applications. Personally, I still think the 6PR would be a useful item to have around, with or without shortcuts. Increased computing power and display resolution could still make a fine product, and the cost of conventional VNAs is certainly prohibitive for many small companies. All I need now is for someone to tell me there already is one.

Returning to the 8410, it is worth noting that HP did much more than provide the microwave community with a fine instrument. It also did a thorough job in promoting the whole concept of *s*-parameter design through its application notes and seminars. This created a legacy of what could be termed "50-Ω engineering," where microwave design using active components became a rather inflexible process of matching individually characterized devices into 50-Ω source and load terminations. It steered us away, in effect, from using multiple connections of individual transistors, techniques that are widespread in analog integrated circuit design at lower frequencies. This culture conflict is becoming more evident as wireless communications drives us to higher levels of integration in our RF IC designs. The "one-transistor amplifier" culture has become more of a hindrance in recent times and is leaving some of the older-generation microwave designers out in the cold. I intend to pick up on this topic in a future column.

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