Microwave Bytes

Probing Times

■ Steve C. Cripps

I frequently get asked whether I find myself running out of things to write about in this column. It's a very simple question to answer, yes I do. When I started writing Microwave Bytes over two years ago, it seemed that by the time I finished one submission, usually sometime late on the deadline date (fortunately extended by my European location), I already had an embryonic idea about what the next one might be about, but that luxury was rather short-lived. I rather think this must be much the same for "real" journalists who write regular (even daily, my gosh) columns, and I suspect we all essentially get bailed out at the 11th hour by the "deadline effect"; that is you sit in front of a keyboard and start typing something, with almost no forethought. The result, for me, is that one basically starts typing about whatever first enters your head, which usually relates to something you have been doing recently. So be it, and once again I find I can string something together. Long may it continue, I guess.

So what have I been up to this last couple of months? A common thread, and as good of a starting point as any other that comes to mind, is something of a microwave workhorse illustrated in all its glory in Figure 1. Yes, it's a rather bent-up piece of semirigid SMA cable with a connector on one end and what I might refer to as a *universal interface* at the other. A picture is better than a thousand words, they say, and I don't think I need to elaborate on what I mean by a universal interface. Closer inspection of this particular specimen will further reveal that it was obviously made in a hurry. Mr. Holmes would probably suggest to Dr. Watson that it was done in some kind of a panic, noting that the inner conductor had been badly scored and the end of the cable considerably disfigured by the use of an inappropriate blunt instrument, something that came to hand at the desperate moment of creation. Yes, I think many readers will empathize, here is a classical tool of the trade, the telltale accoutrement of a microwave engineer who is in a spot of trouble. I will call it the SMA universal interface (SMUI).

Unfortunately, making a decent 50-Ω interface somewhere in the middle of an RF assembly can be hazardous, depending on the level of intrusion that is being allowed.

I submit without hesitation, that I have indeed recently been making much use of the said item in its trouble-shooting mode. But as I think about it, this simple device has a number of uses, all of which seem to have intersected my own world

Figure 1. *The SMA Universal Interface ("SMUI").*

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

Digital Object Identifier 10.1109/MMM.2008.930689

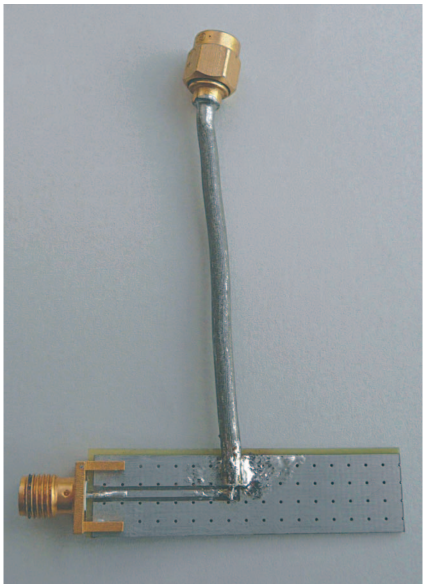

Figure 2. *SUI to RF board interface.*

of late. Indeed, it transpires that with some small modifications I have seen it climb into some esoteric territory, well beyond anything I had ever imagined. More on that shortly, but first a few words about the basic applications. I mostly use such a device as a makeshift 50-Ω interface, usually in an unplanned intrusion into a subsystem that was all supposed to work first time (first-pass design success…yeah tell us about it)—but doesn't. So we have to start testing the performance of individual stages or elements which in truth probably should have been tested and characterized individually before the system assembly was put together on a computer aided design (CAD) system, but management could not afford the time. So now, instead, they have something that is on time but doesn't work, and will probably take more time to fix than it would have taken to do the job properly in the first place. Such is life in the wonderful corporate world, where designers are back-room staff who drink Budweiser and fly coach class. Oh well, at least we can remain honest citizens. I digress.

Unfortunately, making a decent 50-Ω interface somewhere in the middle of an RF assembly can be hazardous, depending on the level of intrusion that is being allowed. Once again, in the first instance we are probably told we can't deface the assembly by cutting pieces out of it, Oh no, they are expensive and spares could not be afforded (unlike business class tickets for those in charge…sorry.…), but I have experienced situations where the interface is as suspicious as the malfunctioning stage it is being used to measure. A typical physical specimen is shown in Figure 2, and the corresponding return loss plot in Figure 3. I must say this result is a good deal better than I expected, probably in large part due to the generous provision of through-vias on the topside of the board.

Another widespread use of the SMUI is the "RF sniffer," typically used in conjunction with a spectrum analyzer to track down the source of undesirable spurious products, be they harmonically related or otherwise. In such a mode, the SMUI takes on a role as an antenna, and is assumed to have some sort of broadband response, but I don't think I have ever seen such a thing as a calibrated SMUI. It so happens that I have recently been taking quite a close look at SMUIs, and some close derivatives, with a view to doing just that; in effect to develop a nonintrusive method of probing internal voltages in RF devices subassemblies. I certainly don't claim to be the first to go down this well trodden path, and of course there are some commercial offerings around, but making the simple transition from a hand-held wave to a precise XYZ positioning system, and affording the SMUI itself a little more care and precision in its construction, produced some interesting results.

Figure 4 shows a swept frequency response for an SMUI made from a regular piece of 0.140″ (3.5 mm) semi-rigid cable. The business end of the SMUI is positioned a short distance above a well-terminated length of microstrip line. In this case, a small refinement has been made in that the end of the SMUI is faced off to be flat, with no protruding inner conductor. Not bad, one might say, despite the slightly flattering 10 dB/division scale. Clearly there is a low end

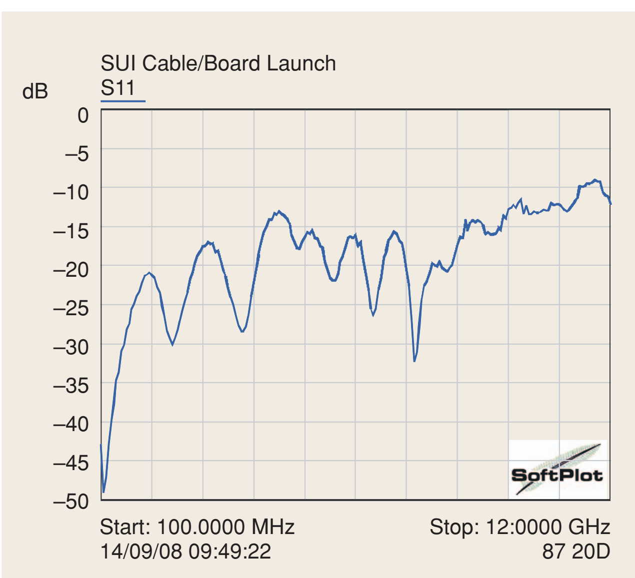

Figure 3. *Input return loss of SMUI to RF board interface shown in Figure 2.*

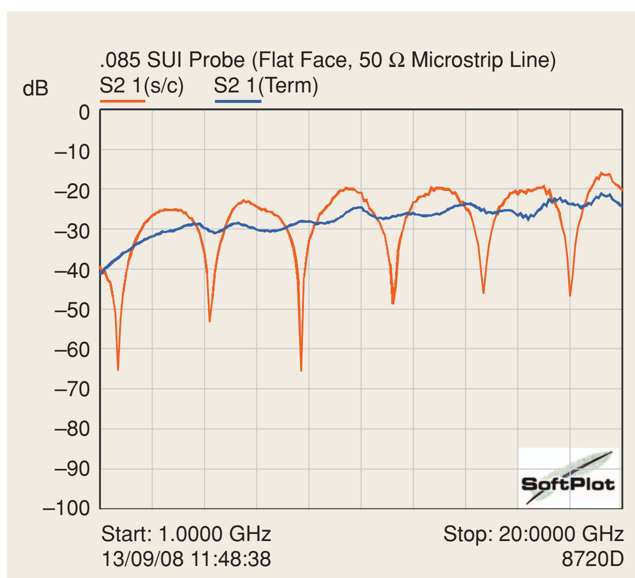

Figure 4. *Microstrip "sniffer" probe response, terminated line (blue trace) and short-circuit terminated line (red trace).*

roll-off due to insufficient capacitive coupling, but above about 1 GHz the probe seems to give a tolerably constant indication of voltage with frequency. Did I say voltage? Well, yes, there hangs a potentially lengthy (and ongoing) debate, but I always like to cut the debate somewhat short by removing the load from the test section of microstrip line, giving the second response as shown in Figure 4. Here we see a regular and familiar VSWR pattern, with the probe duly recording deep nulls at the voltage minima. Although maybe not a completely watertight argument, I always feel that this simple test goes a long way towards proving that the probe responds to the local voltage, and hardly at all to the current. Indeed, I suspect that some of the smaller wiggles in the terminated response themselves correspond to imperfections in the termination.

EM simulators have, up to a point, reduced the need to make detailed field maps of microwave structures, but there is still a clear diagnostic application which seems to have been missed.

It should be said at this juncture that such probes have been used and reported in the microwave literature sporadically for some decades [1]–[3] and in particular before electromagnetic simulators became widely available. EM simulators have, up to a point, reduced the need to make detailed field maps of microwave structures, but there is still a clear diagnostic application which seems to have been missed. Instead of cutting and sawing your way into that troublesome subassembly, why not couple in through a pair of noncontacting probes? One can of course argue that if the selected coupling point has a high VSWR then the results will not necessarily be the same as the more popular invasive approach. But then again, if the VSWR in an internal feedline is high, this may be part of the malfunction and can even be explored by moving the probe up and down the line, slotted line style. In fact, to make such a technique practical it would be necessary to have some means of spacing the probe face from the test board; some further details and information on this topic are in an *ARFTG* presentation I gave in November 2007 [4].

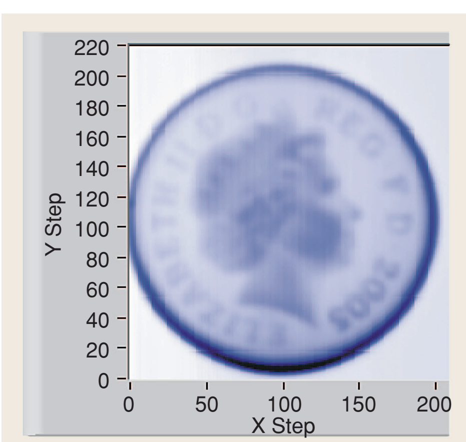

Figure 5. *4.5 GHz microwave microscope coin image (courtesy High Frequency Electronics Institute, Cardiff University, Cardiff, U.K.).*

One of the other issues that comes up with noncontacting probe techniques is spatial resolution. Intuitively, one imagines that the probe is responding to a voltage distribution on the target structure, and registers some kind of a spatial average. This, I am still in the process of discovering, is not necessarily true. Indeed, even the VSWR plot in Figure 3 gives some indication that the probe must be responding to a smaller length of line than its physical size, otherwise the nulls would not be so deep. This however is mainly due to the uniform properties of the transmission line structure which is being probed. In general, the resolution of the measurement will be limited by the size of its physical aperture, and unfortunately as this aperture is reduced, in pursuit of higher resolution, the probe output drops dramatically. This is not such a big problem when probing high power circuits, but stray pickup on the outer of the cable will ultimately intrude too much into the measurement.

Recently, while pondering ways of overcoming the basic tradeoffs in order to obtain higher resolution, I happened to attend a research seminar at Cardiff University in the UK, and the subject was "microwave microscopy." I can't say I had ever heard of such a thing, and I was truly startled when shown the image reproduced in Figure 5. This is an image taken of a British 10 pence coin, which isn't too much different from a US quarter in size, and of late about the same value. To my utter astonishment, the image was made at 4.5 GHz using a probing structure rather similar to my SMUI, using a measurement setup as shown in Figure 6. The main difference is that rather than terminating the thing with 50 Ohms, a gap is made in the inner so that the probing structure becomes a resonator. With this arrangement, the resonant frequency is exquisitely sensitive to anything that is placed in the vicinity of the open end. By measuring the shift in the resonance, using a network analyzer, the surface profile of a specimen can be plotted out. Remarkable, I thought, and surely another paper dart for me to throw at the metamaterial community, who seem to get terribly excited when they claim to have demonstrated rudimentary focussing of low-Ghz microwave radiation. The resolution in Figure 5 is about 100 microns, or two thousandths of a wavelength.

As always, there is a bit of scope for the cynic, who would remind us that a somewhat higher resolution image could be made at optical frequencies using a device called a camera. Imaging coins is not of course the main application for microwave microscopy, but it serves as a startling demonstration of the technique; there are in fact widespread applications in metallurgy, pharmacology and biochemistry. Others may attempt to throw cold water by asserting that this is all "near-field" behavior, but I say so what, I still find it a remarkable result. This has something to do with the fact that it is a new concept for me, and most of the published literature on microwave microscopy is to be found in physics, rather than IEEE journals [5], [6]. Recently reported work, with relatively minor modifications to the basic probing structure, are claiming resolutions in the sub-10 micron regime, and I am still actually trying to get my brain around how they pull off such a feat (there is no question they can do it, the literature is quite abundant). I suppose one can make some general comment to the effect that it has quite a lot to do with how accurately we can measure frequency. If we can register changes in the resonant frequency of the order of kHz, this represents a precision of .0001% at low GHz frequencies, rather better than a micrometer type of measurement device. As a vintage tweaker of microwave circuits, I can certainly believe that moving a metal plane a few tens of microns nearer to an open resonator could indeed shift the resonant frequency by an easily-measurable amount. But how come this arrangement is also able to have similar resolution in the X-Y plane? It seems there is some kind of "focusing" going on, whereby sensitivity in the Z-direction is restricted to an area which is at least one order of magnitude smaller than the outer conductor dimension of the cable.

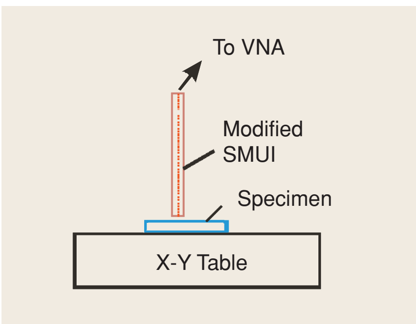

Figure 6. *Microwave Microscope setup.*

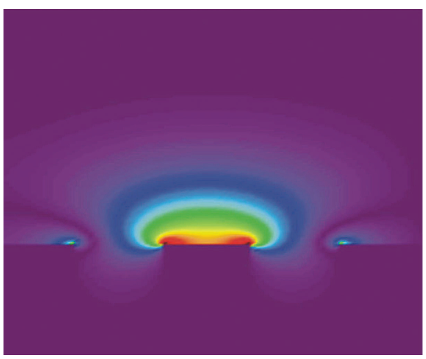

Figure 7. *Electric field distribution at flat open end of an SMA cable (vertical component only).*

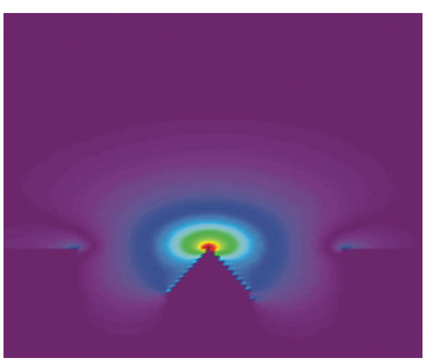

Figure 8. *Electric field distribution at sharpened open end of an SMA cable (vertical component only).*

Voltage is the basic iteration parameter, but one feels intuitively that electric field intensity might be a bigger player in this kind of a problem.

I have to think that the solution to this puzzle lies in the way the electric field contorts around the open end of the probe, particularly if the inner conductor is sharpened. In pursuit of some deeper understanding, I started casting around for a suitable field solver. Here I encountered the familiar problem. I can't justify spending thousands of bucks on a piece of commercial software that I only need to use once (well, a few times but just the one problem). I also have to subject myself to a much-dreaded (for me) learning curve. So I had to consider alternatives. Given the axial symmetry of the SMUI probe, I figured that it should be sufficient to analyze a 2-dimensional cross-section. Many years ago I was faced with a similar modeling problem, and this (dare I say it) was well before the days of commercial EM software, and only barely into the PC era. Once again, I confounded my colleagues and managers by using a resistive analog approach. I went down to the local electronics surplus store and picked up a roll of old chart recorder paper, which had a backside that was a resistive carbon film, about 1kΩ per square. Using silver paint, I was able to determine the characteristic impedance of my "unconventional" transmission line structure in a matter of an hour or two.

Such techniques have been around for well over a century, and were still widely used in the pre-digital era. I remember seeing a wonderful device called an "electrolytic tank" being used to model the complex electric fields inside a travelling wave tube electron gun. It was quite entertaining, and indeed instructive, to watch the iron filings move exquisitely into nature's prescribed patterns. How boring that we now just enter the structural description and wait for the computer to display the result (which can still take a good deal longer than the iron filings). I still have that reel of resistive paper in my possession but, no doubt to the great relief of my readers, I decided there comes a time to jump reluctantly onto the digital bandwagon. So I wrote a very simple program which quickly started giving me some interesting answers. It is possible to solve any static electrostatic field problem using an iterative form of Laplace's equation. If we define a rectangular matrix of points, each having a voltage $V(j,k)$, Laplace's equation boils down to forcing the condition

$$V(j,k) = (1/4) * (V(j,k-1) + V(j,k+1) + V(j-1,k) + V(j+1,k))$$

throughout the air space between the conductors, whose voltage distribution can be set up initially and forced to remain constant. I watch this and think, well, this is basically a "slo-mo" replay of what Nature actually has to do. It typically takes a few hundred complete iterations to get somewhere near a stable solution, but it's interesting to watch the solution emerge. Such a routine can be implemented in just about any programming language, although some run a lot faster than others. I even thought of using an Excel spreadsheet, but displaying the cell values in graphical form is something I have yet to figure out how to do. So my esteemed academic colleagues helped me set it up using a commercial mathematics software package (Igor in this case).

The question quickly emerged: what to plot? Voltage is the basic iteration parameter, but one feels intuitively that electric field intensity might be a bigger player in this kind of a problem. But then there's that wretched vector business, how to display magnitude and direction in a single plot. I decided however that since most of the "action" in a microwave microscope probe is in the "vertical," or axial plane, maybe plotting the intensity of the vertical field component might give the best clues as to what's going on. So Figure 7 shows the vertical field intensity for a basic flat-ended SMUI probe, having a fixed voltage applied across the inner and outer conductors. We see a field pattern that could be imagined as the "radiation pattern" of a near-field antenna. It always seems easier to show the field pattern for a radiating element, rather than figure out what happens in receive mode, since reciprocity says both are one and the same (I perceive that antenna folks play this game all of the time). The interesting comparison however is shown in Figure 8, which shows the same plot for a probe with the pointed inner conductor. Clearly, on a borderline quantitative basis, one can reasonably conjecture that the pointed probe will have a higher resolution in the horizontal plane, possibly by as much as an order of magnitude.

This is actually in line with the 100 micron resolution shown in the Figure 5 image, although one still has to wave the hands a bit and suggest that in the end it does come down to the extreme precision with which the resonant frequency can be perturbed and measured. In using such a probe in a more basic "passive" mode, I don't think I can expect such high resolution, but may yet raise the level of achievement for the humble SMUI to dizzier heights than most would have ever imagined.

I would like to thank Prof. Adrian Porch, of Cardiff University in the UK, for initiating me into the world of microwave microscopy, and providing the Figure 5 image and associated details; he may have a new recruit. Jonathan Lees and Aslam Sulaimalebbe are also thanked for help with the field plotting program.

References

[1] J.S. Dahele and A.L. Cullen, "Electric probe measurements on microstrip," *IEEE Trans. Microwave Theory Tech.*, vol. 28, no. 7, pp. 752–755, July 1980.

[2] Y. Gao and I. Wolff, "Miniature electric near-field probes for measuring 3-D fields in planar microwave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 46, no. 7, pp 907–913, July 1998.

[3] R.H. Annandale, and J.E. Carroll, "Miniature ultra-broadband voltage probe," *Electron. Lett.*, vol. 11, nos. 25/26, pp 620–621, 11 Dec. 1975.

[4] S.C. Cripps, "A broadband non-intrusive voltage probe with LSNA applications," in *Proc. IEEE Conference on Automated RF Techniques*, Tempe, 2007 [CD-Rom].

[5] A. Tselev and S.M. Anlage, "Broadband dielectric microwave microscopy on micron length scales," *Rev. Scientific Instr.*, vol. 78, no. 044701, 2007.

[6] L.A. Valiente, A.A.P. Gibson, and D.A. Haigh, "Tapered coaxial microwave probe sensor," *Electron. Lett.*, vol. 40, no. 23, pp. 1483–1484