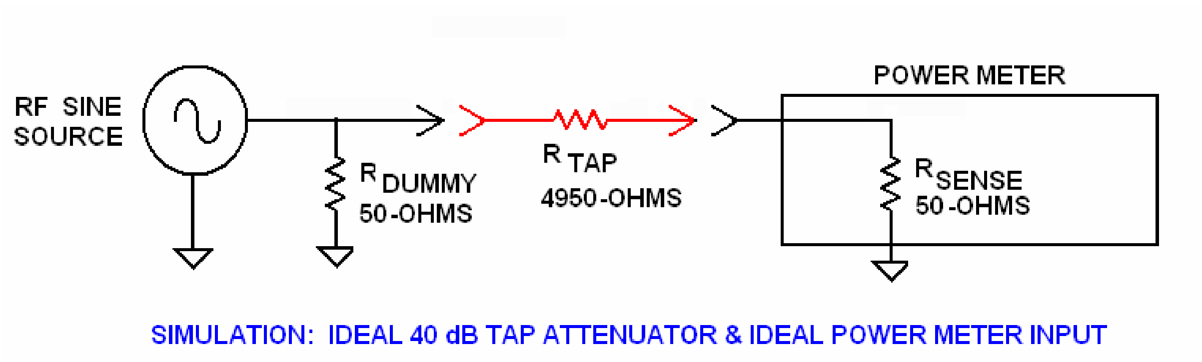
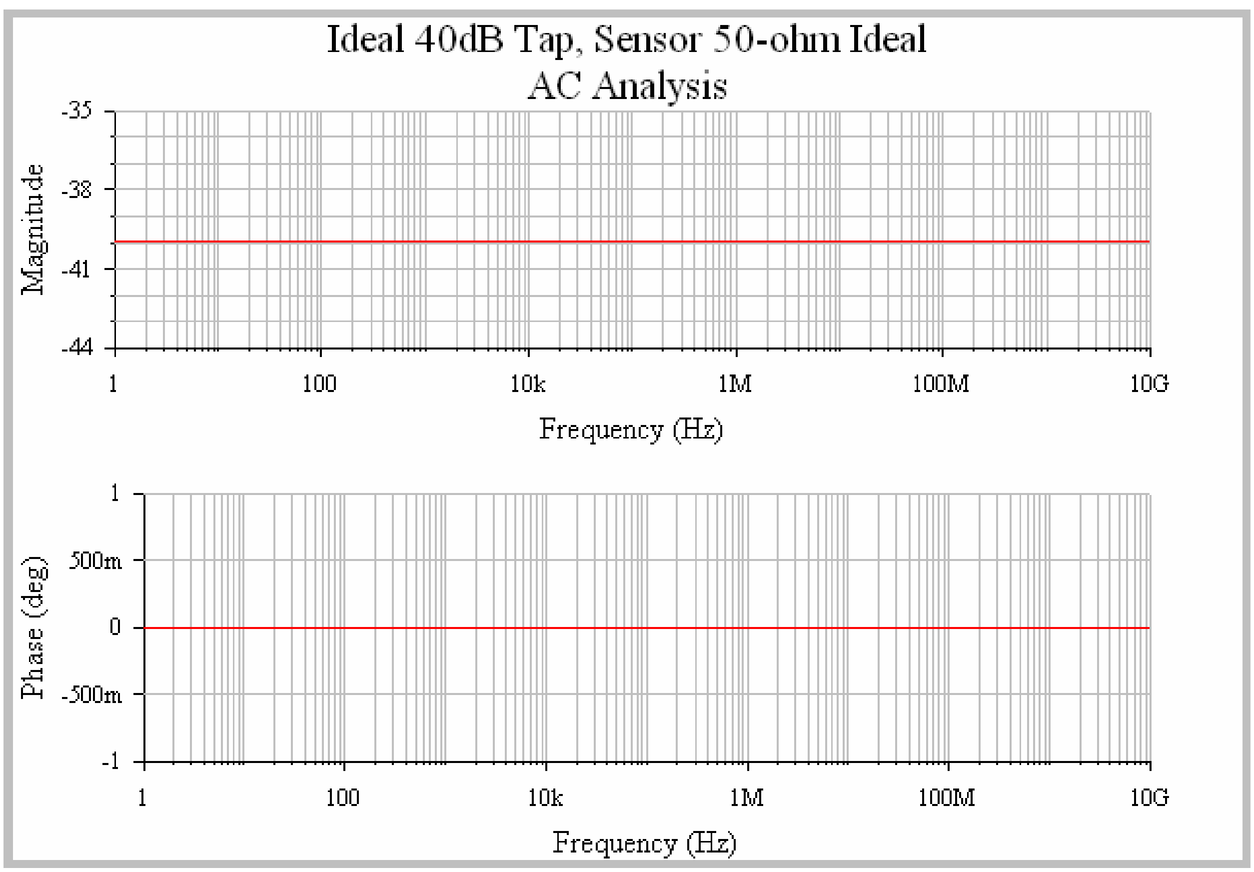
Simulating the 40 dB Tap Attenuator

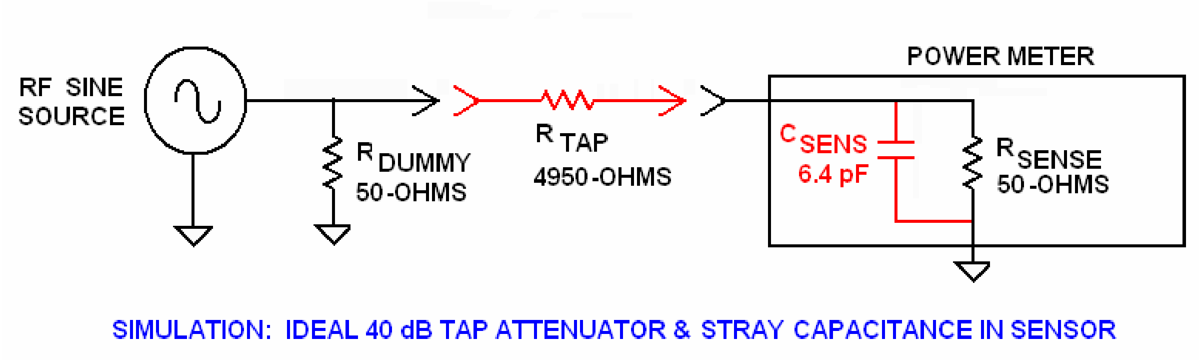
In the first SPICE simulation, we look at the 40 dB tap attenuator with ideal components, while ignoring stray reactances. Here's a schematic of our simulation:



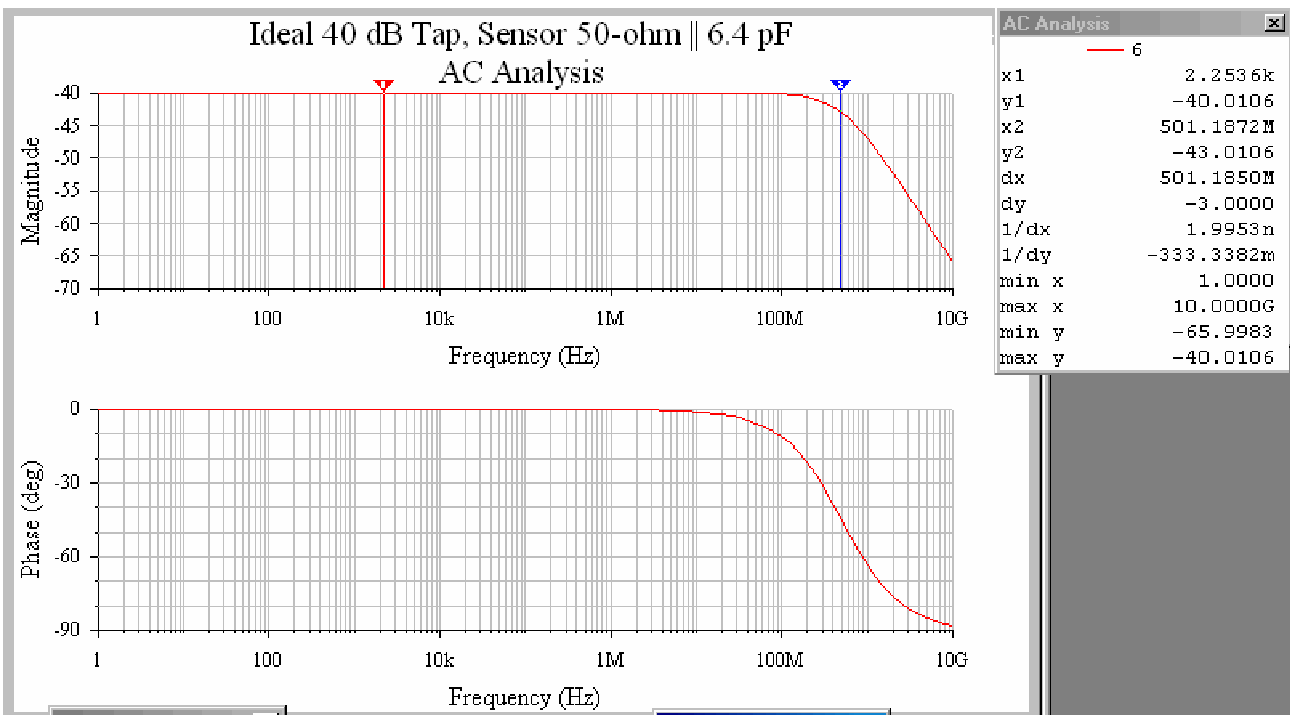
Using an analysis module (a software feature), we compare the voltages at the input and output, where the output (E_{Out}) is considered to be the R-SENSE voltage. Then we plot the results, E_{in}/E_{Out}, expecting to see a flat plot across the frequency spectrum, equal to -40dB. (And we do):



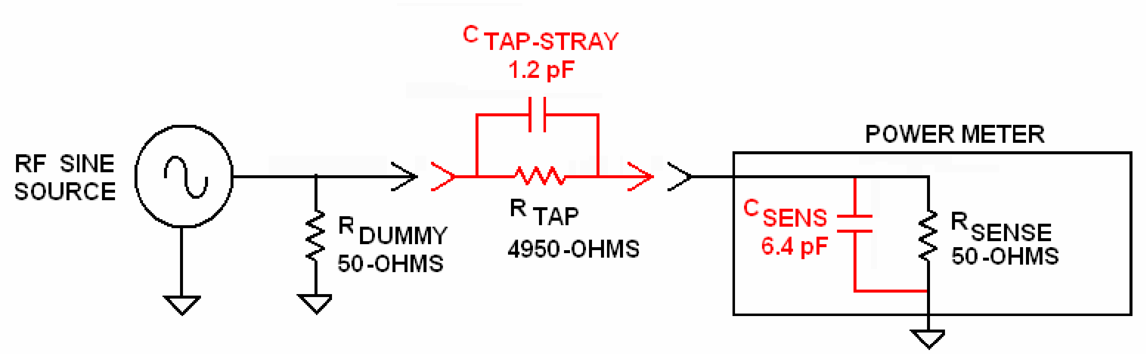
But now we consider that the Power Meter's input circuit has stray capacitance, and we estimate that to be 6.4 pF, shown in red below.



Now our simulation shows the effect of that capacitance is to cause a "rolloff" of the high-frequency response, which we can see in the simulation below. In our example, the -3 dB point is seen to be around 500 MHz, marked by the blue cursor, while the center-band attenuation is seen to be very close to our nominal -40 dB. Incidentally, this rolloff agrees closely with the manufacturer's specified frequency limit for our real-world power meter (the M-Cubed Electronics FPM-1).

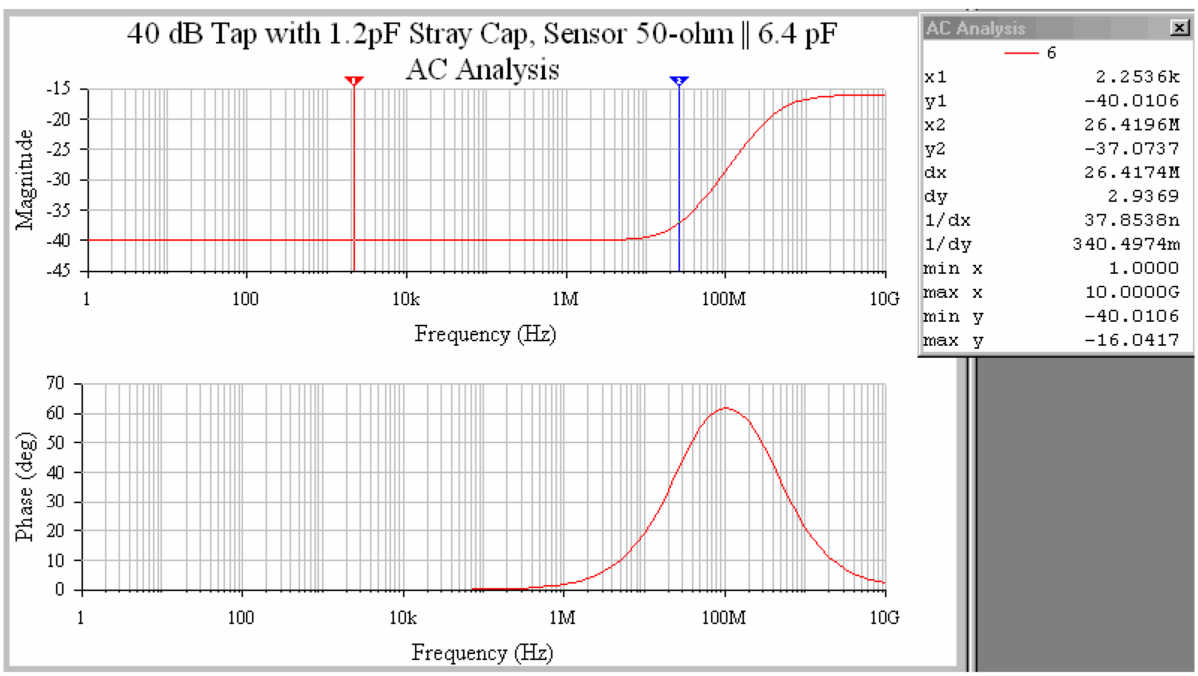


We have yet another stray capacitance we haven't considered yet, that of the tap itself. As can be seen in the schematic below, $C_{TAP-STRAY}$ and C_{SENS} form a voltage divider of their own, but the division ratio is not 40 dB, and that leads to trouble.



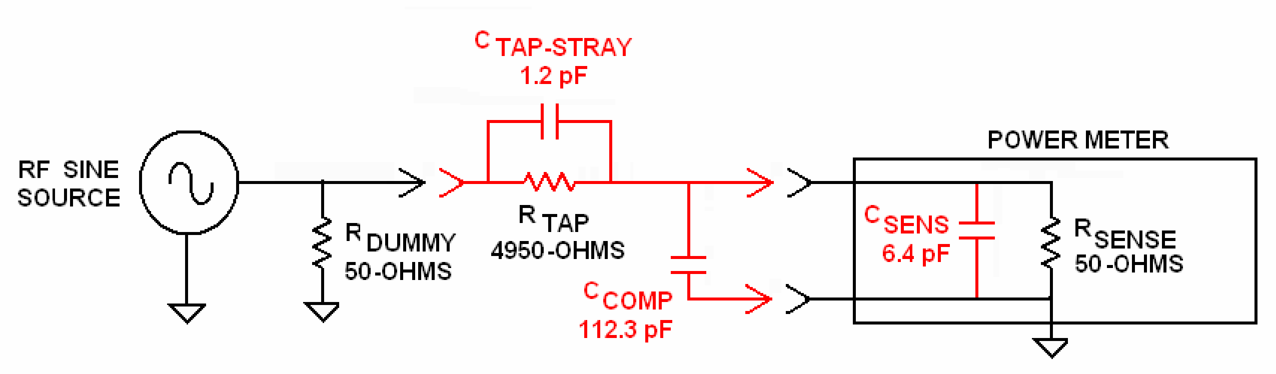
SIMULATION: IDEAL 40 dB TAP ATTENUATOR & STRAY CAPCITANCES

This capacitance allows some coupling of high frequency energy *around* the tap resistor (R_{TAP}) - the higher the frequency, the more unwanted coupling. The effect is to drastically undercut our 40 dB attenuator, causing it to be quite something else at mid-to-high frequencies.



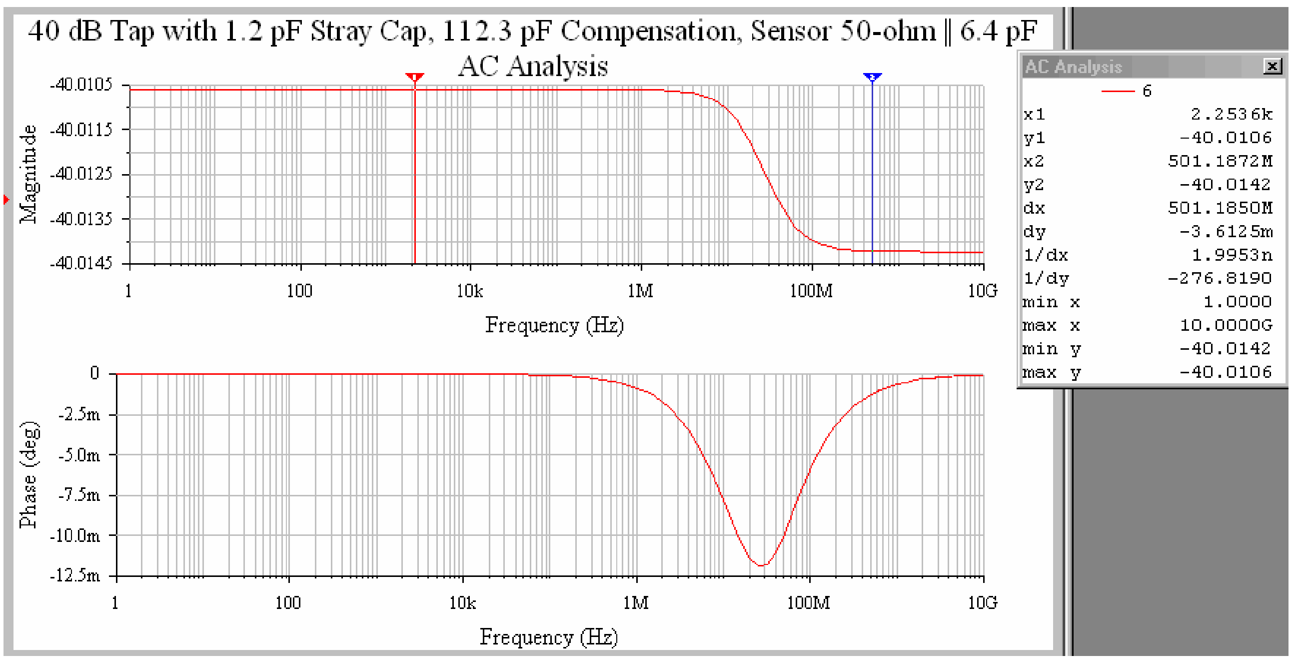
In fact, this is the effect we observed when we first built our 40 dB Tap, without any compensation. Signals at 26 MHz were seen to read 3 dB higher than they should (as indicated by the blue cursor). Our Power Meter is capable of measuring to within +/- 1dB up to 500 MHz, but at this point our homebrew tap will begin adding significant errors as low as 9 or 10 MHz. Completely unacceptable for our application, because we wish to use the device through at least 150 MHz, while preserving the basic meter measurement capabilities.

The classic approach to compensating a resistive tap is to add a capacitor at the sensor side of the tap. When added in parallel to the stray capacitance already in the sensor input, and if its value is selected correctly, it forms a capacitive voltage divider with the same division ratio as the resistive divider, i.e., -40 dB. For our simulation, we add an additional 112.3 pF. In practice (i.e., in the real tap attenuator), we use an 82 pF fixed capacitor and a 120 pF trimmer capacitor, which allows us to adjust the response in situ, for flattest response across the range. For now, don't worry about the number, just trust me. I'll explain later how I came up with those.



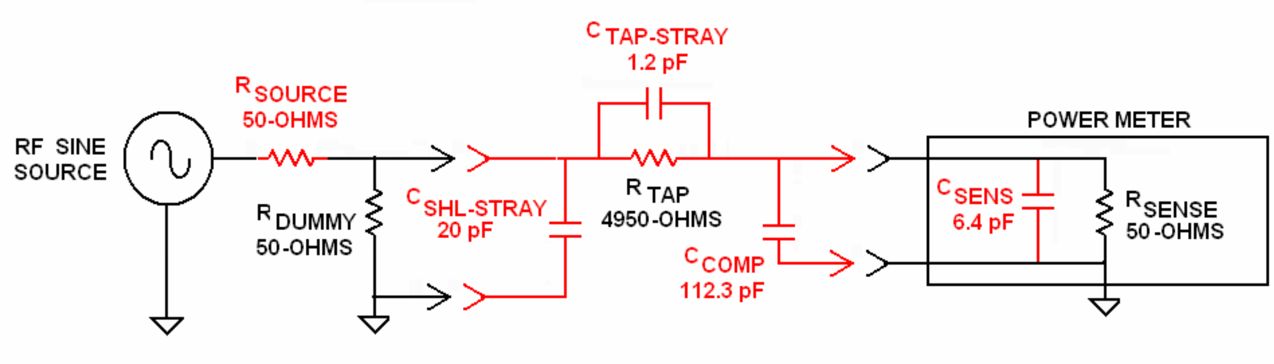
SIMULATION: IDEAL 40 dB TAP ATTENUATOR & STRAY CAPACITANCE IN SENSOR

Now, look how the addition of C_{COMP} flattened our meter response completely (in our simulation):



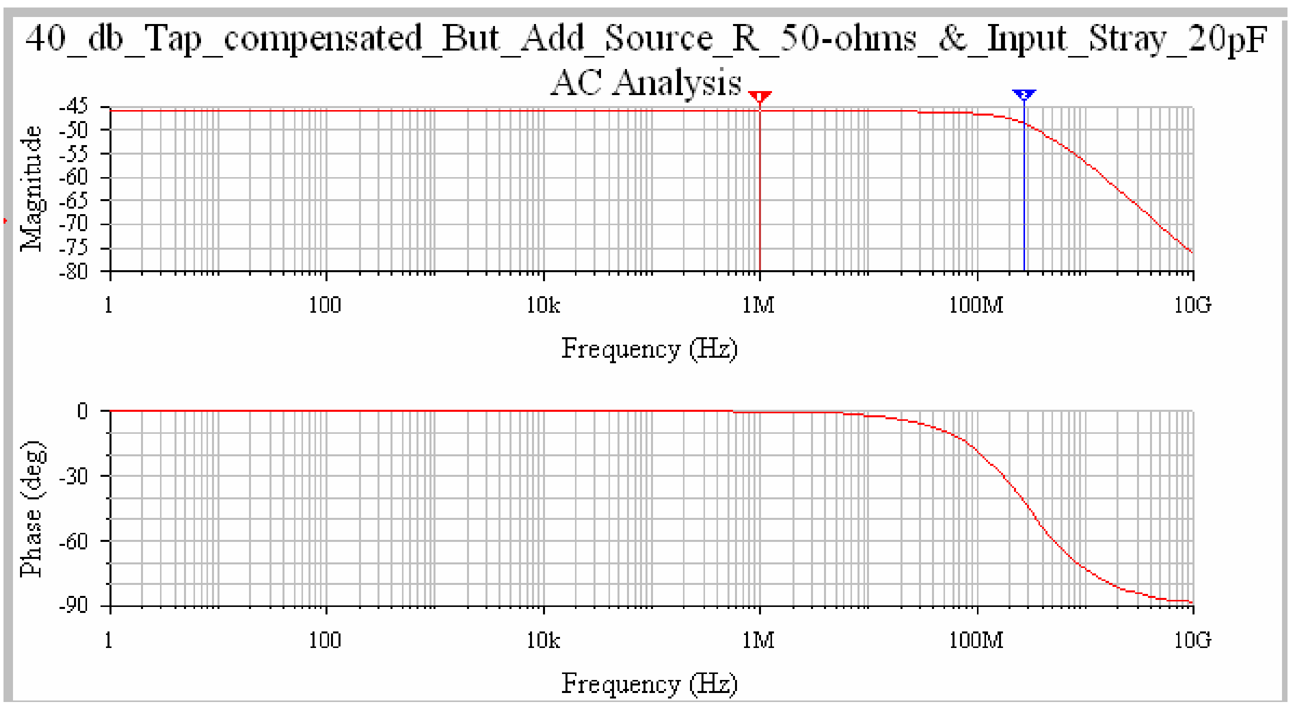
While there is a little hitch in the response, because the vertical scale is zoomed WAY in, we see that the hitch is less than 0.01 dB, much much less than our meter's basic accuracy, and for all practical purposes, flat (to 10 GHz). Alright! Oh… of course, that "flat to infinity" might be too good to be true… and it is…

We've still overlooked some significant stray reactances. In the construction of the 40 dB tap, there are stray couplings to the shield which surrounds it, and series inductances which we haven't accounted for. All of these will serve to add very minor ripple in the response, and limit the high frequency response. But the chief culprit is the distributed stray capacitance to the shield, and so we'll model that as $C_{SHL\text{-}STRAY}$, as shown below:



SIMULATION: FULLY COMPENSATED 40 DB TAP ATTENUATOR WITH KEY STRAY CAPACITANCES

You probably noticed the addition of R_{SOURCE} also, which represents the internal impedance of our signal source. We assume 50 ohms, which would be a conjugate match to the dummy load for maximum power transfer. We've ignored it up until now, but here it becomes a factor, because together with $C_{SHL\text{-}STRAY}$, it adds more rolloff at the high frequency end, and pretty much determines how high in frequency we can predictably use our tap attenuator.



As you can see, the -3 DB point is just under 200 MHz, and the -1 dB is about 150 MHz. Also notice the graph now shows the attenuation as -46 dB. This is because there is 6 dB "loss" in the resistor R_{SOURCE}. It's not really a loss, it's just an artifact of source simulation.

How'd I get to those numbers?

I accomplished these SPICE simulation exercises to better understand what the various factors were in the 40 dB Tap operation, and to convince myself it is working correctly, since I don't have a lot of laboratory-grade equipment to prove it my measurement. As a result, I have a lot more confidence in the device, and I now know it's limitations.

Some may wonder how I came up with the various values for the simulation.

R_{SENSE} is specified by the manufacturer as 50 ohms, and I happen to know they hold this to within 1%. But the power meter input capacitance, C_{SENS}, is not specified directly. What we do know is that the manufacturer specifies the upper frequency limit as 500 MHz.

Knowing that the 3 db point of a second order R-C filter is given by the formula:

$$Fc = 1 / (2 \pi R C)$$

And since we know R_{SENSE} and Fc, but we don't know C_{SENS}, we transpose the equation to:

$$C_{SENS} = 1 / (2 \pi F * R_{SENSE})$$

$$C_{SENS} = 1 / (2 * 3.1416 * 500 * 10^6 * 50)$$

$$C_{SENS} = 6.366 \text{ pF}$$

Which is our estimated C_{SENS}, rounded to 6.4 pF.

Next, we needed to estimate our stray coupling capacitance ($C_{TAP-STRAY}$, which appears across R_{TAP}). To do this, we measured the upper NON-attenuating response of our uncompensated tap attenuator. With an ohmmeter, we could measure the tap resistor (R_{TAP}) as 4950 ohms. So we knew at DC and low frequencies, the attenuation would be dictated by the voltage divider factor:

$$Factor = R_{SENSE} / (R_{TAP} + R_{SENSE})$$

$$Factor = 50 / (4950 + 50)$$

$$Factor = 0.01$$

Which, for a voltage ratio, converts to -40 dB by the formula:

$$dB = 20 \log (Factor)$$

$$dB = 20 \log (0.01)$$

$$dB = -40$$

Given the value for the tap resistor (T_{TAP}), if we could measure the uncompensated 3 dB point where the attenuation goes above its nominal 40 dB, we could again apply the formula above to estimate the stray coupling capacitance, $C_{TAP-STRAY}$. To do this, we used a signal generator with a level-controlled output, and raised the frequency until we observed the power reading increase by 3 dB. That frequency was 26 MHz. Now we can apply our formula:

$$C_{TAP-STRAY} = 1 / (2 \pi F * R_{TAP})$$

$$C_{TAP-STRAY} = 1 / (2 * 3.1416 * 26 * 10^6 * 4950)$$

$$C_{TAP-STRAY} = 1.236 \text{ pF}$$

Knowing $C_{TAP-STRAY}$, we could now figure out the total capacitance needed in the capacitive voltage divider to match the 40 dB resistive divider. But capacitive reactance is inversely proportional to capacitance, so that our voltage divider formula now becomes:

$$FACTOR_{CAPAC} = C_{TAP-STRAY} / (C_{TAP-STRAY} + C_{comp})$$

Notice that this is "upside-down" compared to the resistive voltage divider's formula. Now, since we know the factor (-40 dB or 0.01) and the stray coupling $C_{TAP-STRAY}$ (1.2 pF), we transpose the formula to solve for $C_{COMP-TOT}$:

$$C_{COMP-TOT} = (C_{TAP-STRAY} / FACTOR_{CAPAC}) - C_{TAP-STRAY}$$

$$C_{COMP-TOT} = (1.2 / 0.01) - 1.2$$

$$C_{COMP-TOT} = 118.8 \text{ pF}$$

Which is our estimated ***total*** $C_{COMP-TOT}$. But that includes the C_{SENS} capacitance, which is already in the circuit, so we must now subtract to get a value we can install:

$$C_{COMP} = C_{COMP-TOT} - C_{SENS}$$

$$C_{COMP} = 118.8 - 6.4$$

$$C_{COMP} = 112.4 \text{ pF}$$

In our simulation, for reasons unknown, I used 112.3 pF. (So sue me). In the real-world tap attenuator, we install a variable trimmer capacitor of a reasonable value, and adjust for flattest response using our signal generator. In my case, I used a fixed 82 pF capacitor in parallel with an 8-120 pF trimmer, because that's what I had available to fit the space. Since stray reactances can at best be estimated (as we did here), the real-world implementation needs to have a means to "tweak" the attenuator compensation circuitry in order to optimize the response. Hence, the trimmer.