Carl Battjes

10. Who Wakes the Bugler?

Introduction: T-Coils in Oscilloscope Vertical Systems

Few engineers realize the level of design skill and the care that is needed to produce an oscilloscope, the tool that the industry uses and trusts. To be really effective, the analog portion of a vertical channel of the oscilloscope should have a bandwidth greater than the bandwidth of the circuit being probed, and the transient response should be near perfect. A vertical amplifier designer is totally engrossed in the quest for this unnatural fast-and-perfect step-response. The question becomes, “How do ’scope designers make vertical amplifier circuits both faster and cleaner than the circuits being probed?” After all, the designers of both circuits basically have the same technology available.

One of many skillful tricks has been the application of precise, special forms of the T-coil section. I’ll discuss these T-coil applications in Tektronix oscilloscopes from a personal and a historical perspective, and also from the viewpoint of an oscilloscope vertical amplifier designer. Two separate stand-alone pages contain “cookbook” design formulas, response functions, and related observations.

The T-coil section is one of the most fun, amazing, demanding, capable, and versatile circuits I have encountered in ’scopes. Special forms

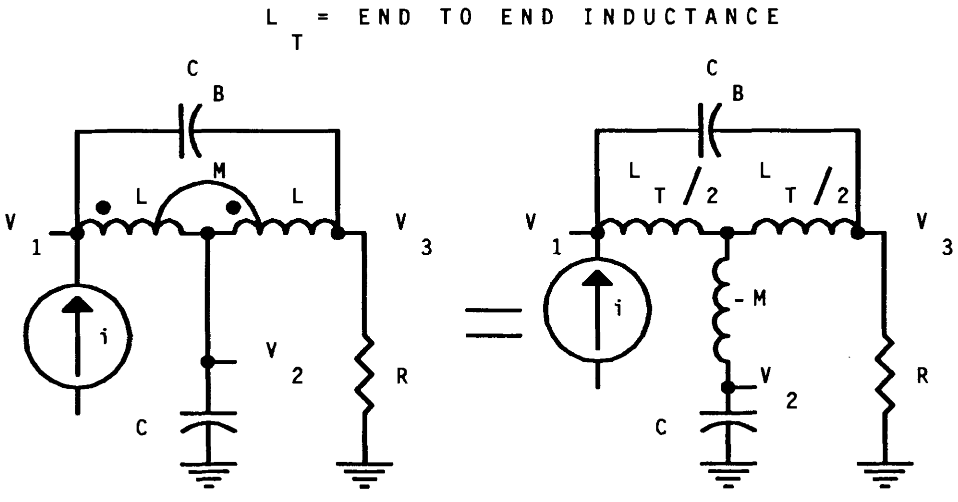


Figure 10–1. The T-coil Section.

of this basic circuit block are used with precision and finesse to do the following:

Peak capacitive loads
Peak amplifier interstages
Form "loop-thru" circuits
Equalize nonlinear phase
Transform capacitive terminations to resistive terminations
Form distributed deflectors in cathode ray tubes
Form artificial delay line sections
Form distributed amplifier sections

I have successfully used T-coils in all of these applications except the last two. Recently, however, some successful designers from the '40s and '50s shared their experiences with those two applications.

Over My Head

While on a camping trip in Oregon in 1961, I stopped at Tektronix and received an interview and a job offer the same day. Tektronix wanted me. They were at a stage where they needed to exploit transistors to build fast, high-performance 'scopes. I had designed a 300MHz transistor amplifier while working at Sylvania. In 1961, that type of experience was a rare commodity. Actually, I had designed a wideband 300MHz IF amplifier that only achieved 200MHz. What we (Sylvania) used was a design that my technician came up with that made 300MHz. So I arrived at this premier oscilloscope company feeling somewhat of a fraud. I was more than just a bit intimidated by the Tektronix reputation and the distributed amplifiers and artificial delay lines and all that "stuff" that really worked. The voltage dynamic range, the transient response cleanliness, and DC response requirements for a vertical output amplifier made my low-power, 50 Ohm, 300MHz IF amplifier seem like child's play. Naturally, I was thrown immediately into the job of designing high-bandwidth oscilloscope transistor vertical-output amplifiers. I felt like a private, fresh out of basic training, on the front lines in a war.

The Two Principles of Inductive Peaking

The primary and most obvious use of a T-coil section is to peak the frequency response (improve the bandwidth, decrease the risetime) of a capacitance load. Inductances, in general, accomplish this through the action of two principles.

Principle Number One: Separate, in Time, the Charging of Capacitances

The coaxial cable depicts a limiting case of Principle Number One. A coaxial cable driven from a matched-source impedance has a very fast risetime. The source has finite resistance and the cable has some total capacitance. If the cable capacitance and inductance are uniformly distrib-

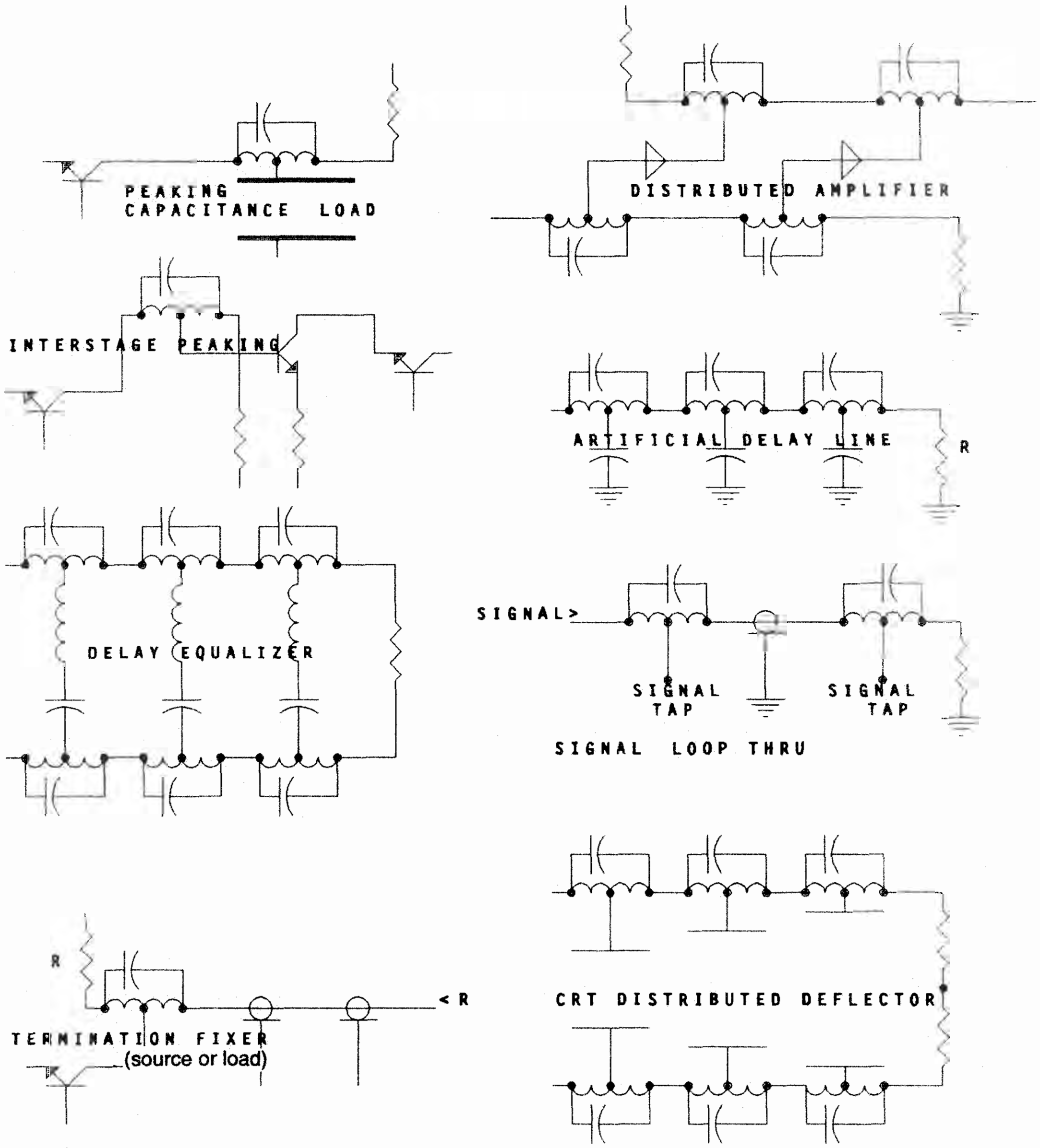
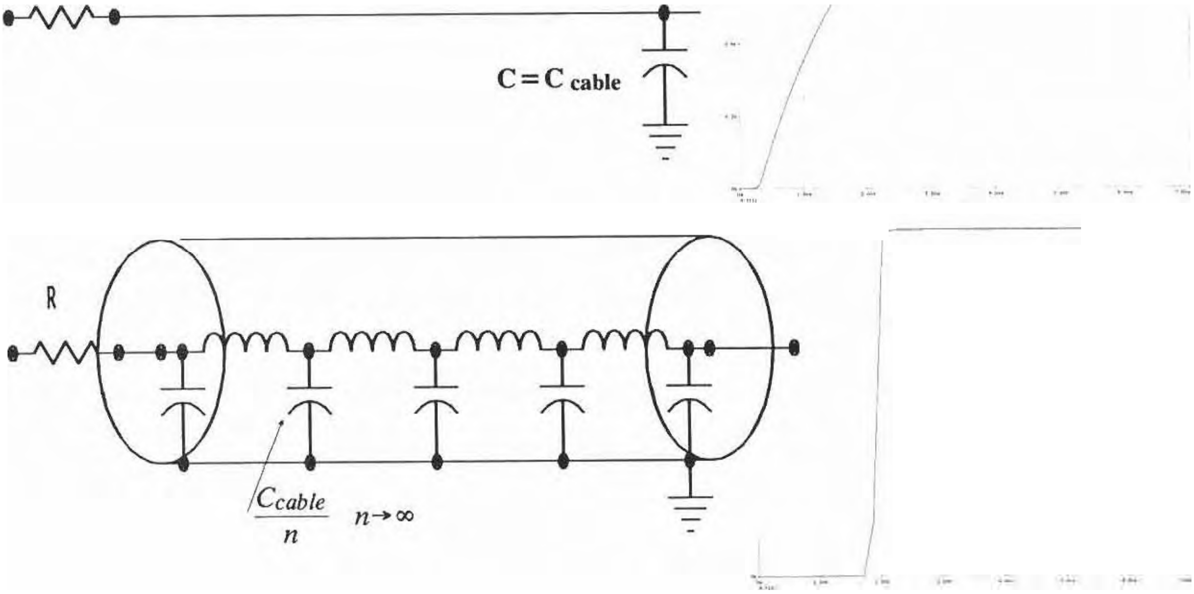


Figure 10–2.
The Versatile T-coil.

uted and the cable is situated in the proper impedance environment, the bandwidth is >> $1/2\pi RC_{cable}$ and the risetime << $2.2\ RC_{cable}$. The distributed inductance in the line has worked with the distributed capacitance to spread out, in time, the charging of this capacitance. A pi-section LC filter could also demonstrate Principle Number One, as could a distributed amplifier.

Figure 10–3. Separate, In Time, the Charging of Capacitances.
Peaking Principle 1



Principle Number Two: Don't Waste Current Feeding a Resistor When a Capacitor Needs to Be Charged In Figure 10–4 a helpful elf mans the normally closed switch in series with the resistor. When a current step occurs, the elf opens the switch for RC seconds, allowing the capacitor to take the full current. After RC seconds, the capacitor has charged to a voltage equal to IR. The elf then closes the switch, allowing the current

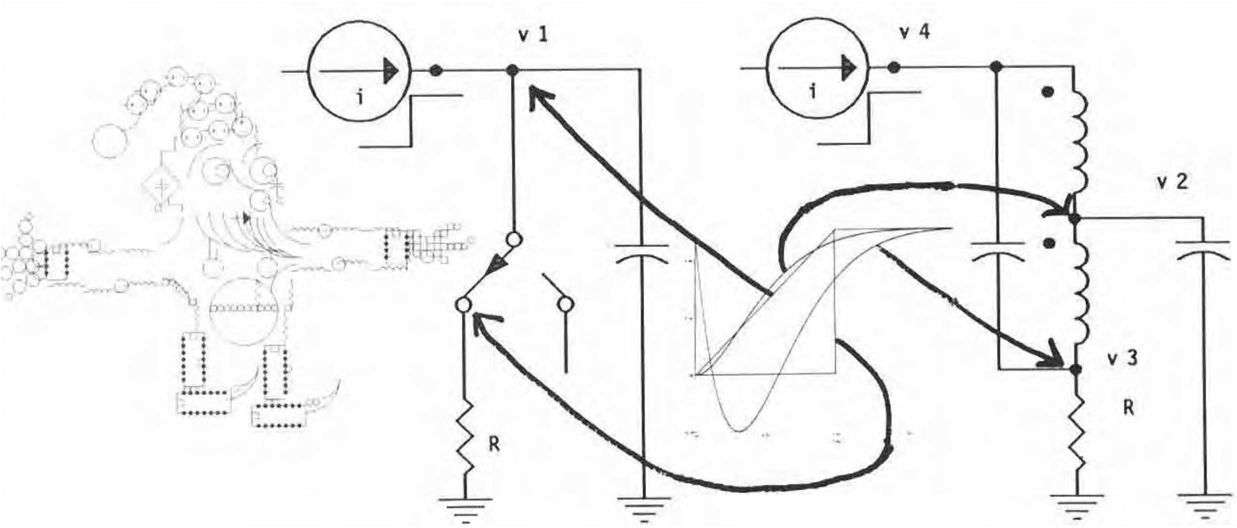


Figure 10–4.
Don't Waste Time Feeding a Resistor When a Capacitor Needs to be Charged.
Peaking Principle 2

to feed the resistor, also producing a voltage equal to IR. No current is wasted in the resistor while the capacitor is charging.

A current step applied to the constant-resistance bridged T-coil yields the same capacitor voltage risetime, 0.8 RC, as the elf circuit. In both cases, during the rise of voltage on the capacitor, the voltage waveform on the termination resistor is negative, zero, or at least low. Without the helpful elf, or without the T-coil, the risetime would have been 2.2 RC. With these risetime enhancers, the risetime is lowered to 0.8 RC. This is a risetime improvement factor of 2.75. If there are two or more capacitor lumps, Principle Number One can combine with Principle Number Two to obtain even higher risetime improvement factors.

When both principles are working optimally, reflections, overshoot, and ringing are avoided or controlled. This is a matter of control of energy flow in and out of the T-coil section reactances. A T-coil needs to be tuned or tolerated. In the constant-resistance T-coil section, given a load capacitance, there is only one set of values for the inductance, mutual inductance, and bridging capacitance which will satisfy one set of specifications of the driving point resistance (may imply reflection coefficient) and desired damping factor (relates to step response overshoot).

T-Coils Peaking Capacitance Loads

A cathode ray tube (CRT) electrostatic deflection plate pair is considered a pure capacitance load. In the '50s and '60s, T-coils were often used in deflection plate drive circuits. Usually a pentode-type tube was used as the driver, rather than a transistor, because of the large voltage swing required. The pentode output looked like a capacitive high-impedance source. A common technique was to employ series peaking of the driver capacitance, cascaded with T-coiled CRT deflection plate capacitance.

The 10–MHz Tektronix 3A6

The 3A6 vertical deflection amplifier works really hard. The 3A6 plug-in was designed to operate in the 560 series mainframes, where the plug-ins drove the CRT deflection plates directly. The deflection sensitivity was poor (20 volts per division) and the capacitance was high. To cover the display screen linearly and allow sufficient overscan, the output beam power tube on each side had to traverse at least 80 volts. The T-coils on the 3A6 made the bandwidth and dynamic range possible without burning up the large output vacuum tubes.

A Real T-Coil Response

A vertical-output deflection-amplifier designer has a unique situation—the amplifier output is on the screen—no other monitor is needed. This is the case with the 3A6 circuit shown here. The input test signal is clean and fast. The frequency and step response of the entire vertical system is dominated by the "tuning" of the T-coil L384 and its opposite-side

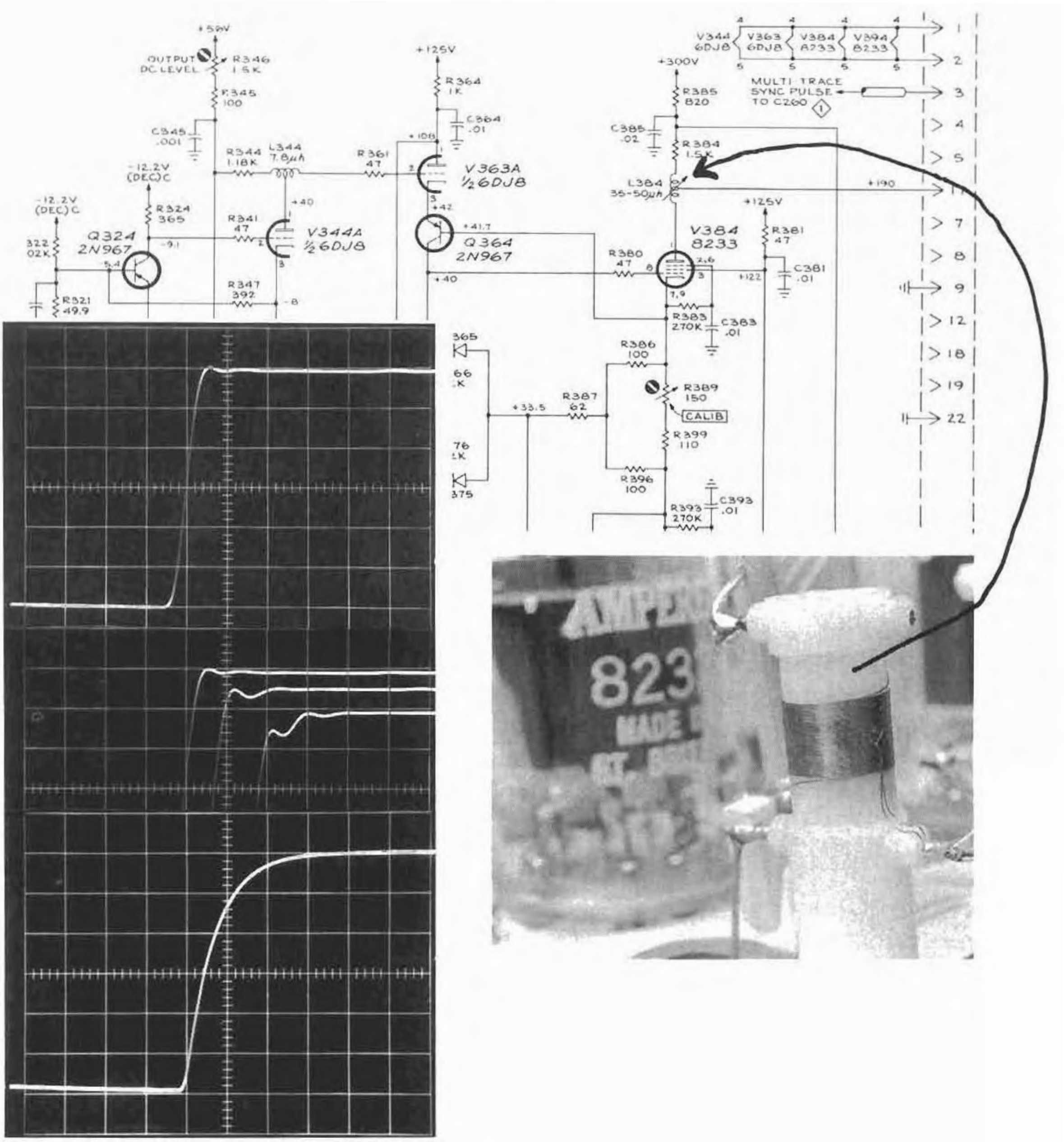
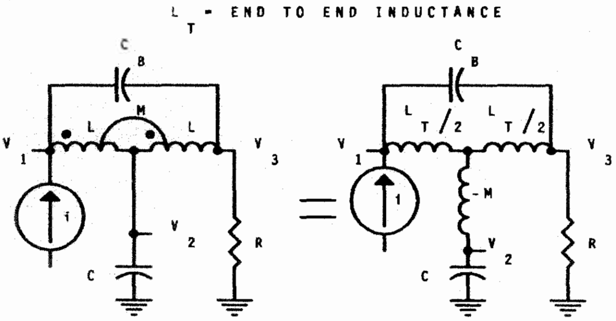


Figure 10–5.
Step Response Waveforms 3A6 T-coil Peaking.

FACT SHEET FOR CONSTANT-RESISTANCE T-COILS



damping factor

$$\delta = \frac{1}{2}\sqrt{\frac{(1+k)}{(1-k)}}$$

$L_T = 2L + 2M$ k=*coupling coefficient* $k=\frac{M}{L}$ and $\frac{M}{L_T}=\frac{k}{2(1+k)}$

If $L_T=R^2C$ and $C_B=\frac{(1-k)C}{4(1+k)}$

Then $\frac{v1}{i}=R$ **the Constant Resistance Property**

and $\frac{v2}{i}=\frac{R}{1+\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}$ **a Quadratic (2 pole) Response at v_2**

and $\frac{v3}{i}=R\,\frac{1-\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}{1+\frac{RCs}{2}+\frac{(1-k)R^2C^2s^2}{4(1+k)}}$ **an ALL PASS response at v_3**

	v_2 step response overshoot
k= .6 (CRITICAL DAMPING)	**0.0%**
k=.5 (FLAT DELAY)	**0.4 %**
k=.333 (FLAT AMPLITUDE)	**4.3%**
k= 0.0 (high frequency DELAY BOOST)	**16.0%**

SPECIAL NOTE ON m-DERIVED T-COILS.

The m-derived t-coils arise from m-derived filter theory. They do not have the constant-resistance property. The total inductance = R^2C. They have no bridging capacitance. They do not have a simple quadratic (2 pole) response. The value of "m" implies a coupling coefficient $k=\frac{m^2-1}{m^2+1}$

Figure 10–6.
Fact Sheet on Constant Resistance T-coils.

counterpart. The bottom picture shows the response when the coils (L384 and its mate) were disabled. (All three terminals of each coil were shorted together.) This reveals that, without the coils, the response looks very much like a single-time-constant response. The middle picture illustrates the progression of tuning after the shorts are removed. The powdered iron slugs in the coil forms are adjusted to optimize the response. The top picture shows the best response. The 10–to-90% risetime of the beginning waveform is 75 nanoseconds, and in the final waveform it drops to 28 nanoseconds. This is a ratio of risetimes of 2.6—near the theoretical bandwidth improvement factor of 2.74. The final waveform has peak-to-peak aberrations of 2%.

The total capacitance at the deflector node includes the deflection plates, the wires to the plates, the beam power tube plate capacitance, the wiring and coil body capacitance, the plug-in connector capacitance, the mounting point capacitances, the chassis feedthrough capacitance, the resistor capacitance, and possibly virtual capacitance looking back into the tube. We can solve for the equivalent net capacitance per side by working back from the 75nsec risetime and the 1.5k load resistance. This yields about 23pF per side. Although each coil is one solenoidal winding, it actually performs as two coils. The coil end connected to the tube plate works as a series peaking coil, and the remainder as the actual T-coil.

L344, which is also a T-coil, appears upstream in the 3A6 schematic fragment. Notice that the plate feeds the center tap of this coil. This is an application of reciprocity (Look in your old circuit textbook!). If the driving device output capacitance is significantly greater than the load capacitance, it may be appropriate to use this connection.

Distributed Amplifiers in Oscilloscopes

The idea of a distributed amplifier goes back to a British "Patent Specification" by W.S. Percival in 1936. In August 1948, Ginzton, Hewlett, Jasberg, and Noe published a classic paper on distributed amplifiers in the "Proceedings of IRE." At about the same time, Bill Hewlett (yes, of HP) and Logan Belleville (of Tektronix) met at Yaws Restaurant in Portland. Bill Hewlett described the new distributed amplifier concepts (yes, he "penciled out" the idea on a napkin!). In 1948, from August through October, Howard Vollum and Richard Rhiger built a distributed amplifier under a government contract. This amplifier was intended for use in a high-resolution ground radar. It had about a 6nsec risetime and a hefty output swing. In order to measure the new amplifier's performance, Vollum and Rhiger had outboarded it on the side of an early 511 'scope, directly feeding the deflectors.

It soon became clear that what the government and industry really needed was a very fast oscilloscope. I am not sure of the details or sequence of events, but Tektronix—Howard Vollum's two-year-old company—was making history. Vollum, Belleville, and Rhiger developed the 50MHz 517 oscilloscope, an oscilloscope with a distributed amplifier in the vertical deflection path. Vollum and Belleville had successfully refined the distributed amplifier enough to satisfy this oscilloscope vertical amplifier application. The product was successful and order

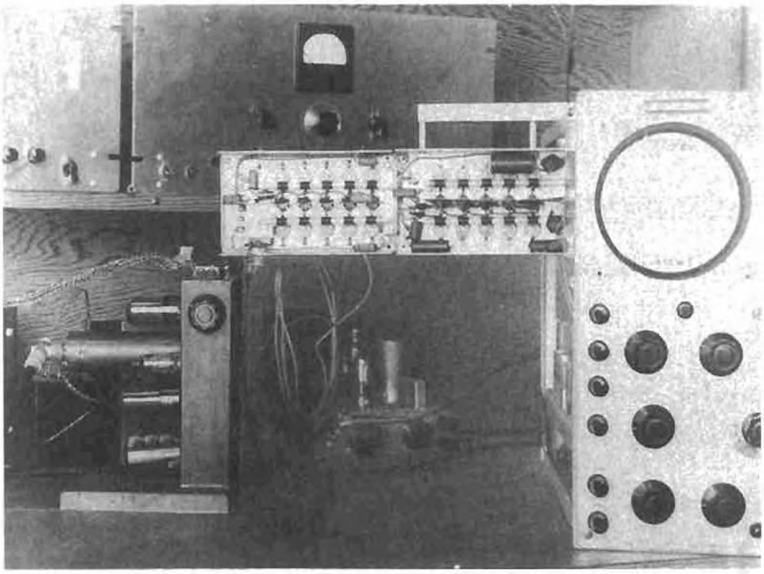


Figure 10-7. 1948 Experiment—Outboarded Distributed Amplifier.

rates exceeded Tek's ability to manufacture. Logan left Tektronix in the early '50s and Vollum and Rhiger were left managing this new big company. John Kobbe, Cliff Moulton, and Bill Polits, as well as other key electrical circuit designers, took up where Vollum, Belleville, and Rhiger had left off. Other distributed amplifiers were designed for other 'scopes during the '50s, including the 540 series at 30MHz and the 580 series at 100MHz.

Manufacturing Distributed Amplifier Oscilloscopes

The whole idea of using a distributed amplifier as an oscilloscope vertical amplifier is rather incredible to me. Obtaining a very fast, clean step response is a hard job. When T-coils are employed, the job is even harder. When they are employed wholesale, as in a distributed amplifier, they are "fussy squared or tripled." The tuning of an oscilloscope distributed amplifier and/or an artificial delay line is tricky. Tuning is done in the time domain, with clues about where and in which direction to adjust, coming from observations of the "glitches" in the step response. If the use of a distributed amplifier in the vertical channel of an oscilloscope was proposed in today's business climate, it would be declared "unmanufacturable." It would never see the light of day. However, the Tektronix boom expansion in the '50s occurred largely through the development, manufacture, and sale of distributed amplifier 'scopes.

The 100MHz 580 series was the last use of distributed amplifiers in Tektronix 'scope vertical systems. Dual triodes, low cathode connection inductance, cross-coupled capacitance neutralization, and distributed deflectors in the CRT helped to achieve this higher bandwidth.

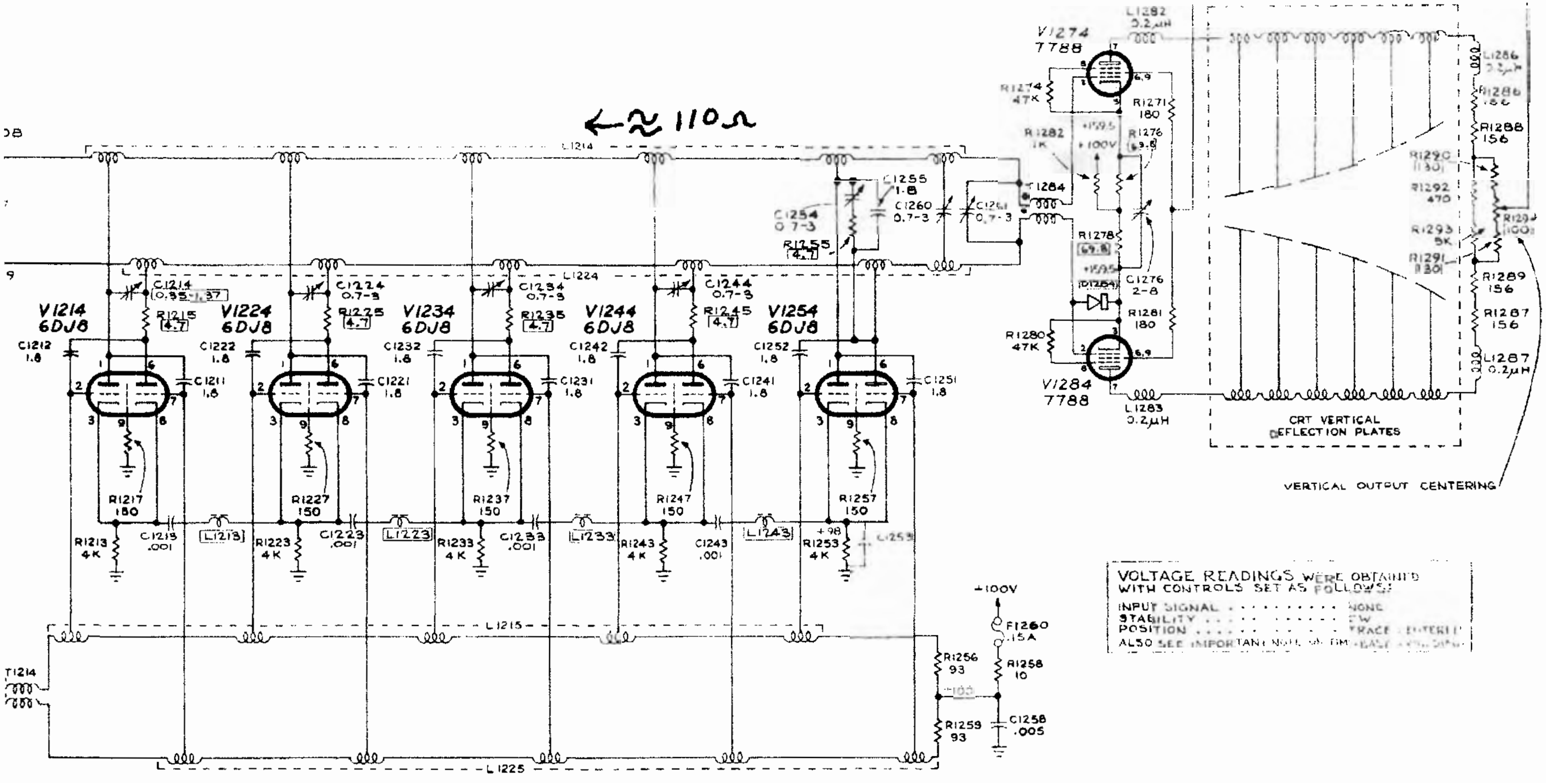


Figure 10–8.
Tektronix 585 Distributed Amplifier Vertical Output.

Distributed Deflector for a Cathode Ray Tube

In 1961, Cliff Moulton's 1GHz 519 'scope led the bandwidth race. This instrument had no vertical amplifier. The input was connected to a 125-ohm transmission line which directly fed a single-ended distributed deflection system. Schematics in Figures 10–8 and 10–9 show somewhat pictorially what a distributed deflector looks like. The 519 deflector is not shown. Within the CRT envelope was a meander line distributed deflection plate. Tuning capacitors were located at the sharp bends of the meander line. The line was first tuned as a mechanical assembly and later incorporated into the CRT envelope.

Terminated distributed deflector structures create a resistive driving-point impedance in place of one lumped capacitance. They also synchronize the signal travel along the deflection plate to the velocity of the electron beam speeding through the deflection plate length. If a distributed deflector is not used, deflection sensitivity is lost at high frequency due to transit time. Relative sensitivity is

$$\frac{\sin\frac{f}{f_{tx}}}{\frac{f}{f_{tx}}}$$

where f is frequency and f_{tx} is an inverse transit time function.

This is usually significant at 100MHz and above, and therefore distributed deflectors show up in 'scopes with bandwidths of 100MHz or higher. Various ingenious structures have been used to implement distributed deflectors. All could be modeled as assemblies of T-coils. The effective electron beam deflection response is a function of all of the T-coil tap voltages properly delayed and weighted.

Theoretical and Pragmatic Coil Proportions

The basis for the earliest T-coil designs was m-derived[1] filter theory. The delay lines and the distributed amplifier seemed to work best when the coils were proportioned—as per the classic Jasberg-Hewlett paper[2]—at m = 1.27 (coupling coefficient = 0.234). This corresponds to a coil length slightly longer than the diameter. In the design phase, there was an intelligent juggling of coil proportions based on the preshoot-overshoot behavior of the amplifier or delay line. The trial addition of bridging capacitance invariably led to increased step response aberrations.

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1. m-derived filters were outcomes of image-parameter filter theory of the past. The parameter "m" determined the shape of the amplitude and phase response. "m"=1.27 approximated flat delay response. Filters could not be exactly designed, using this theory, because the required termination was not realizable.
2. This classic paper described both the m-derived T-coil section and, very briefly, the constant-resistance T-coil section. The use of these sections in distributed amplifiers was the main issue and nothing was mentioned of other uses.

In contrast with the artificial delay lines and the distributed amplifiers, the individual peaking applications usually needed a coil with more coupling (k = 0.4 to 0.5), which was realized by a coil shorter than its diameter. When the coil value is near or below 100 nanohenries, the goal is then to get as much coupling as possible so that the lead inductance of the center tap connection can be overcome. Flat pancake or sandwich coils of thin PC board material, thin films, or thick films are used to achieve high coupling.

The Importance of Stray Capacitance in T-Coils

The stray interwinding capacitance of a T-coil can be crudely modeled by one bridging capacitance C_{bs} across the whole coil. It is defined by the coil self-resonance frequency "f_{res}."

$$C_{bs} = \frac{1}{(2\pi f_{res})^2 L_T}$$

where L_T is the coil total inductance. If C_B is the required bridging capacitance for constant-resistance proportions, then $C_x = C_b - C_{bs}$ needs to be added. This is an effective working approximation. The recent coils built for high-frequency 50 Ohm circuits usually need additional bridging capacitance. On the other hand, the old nominally m-derived circuits never needed any added bridging capacitance. They were high-impedance circuits with very large coils and probably had enough effective bridging from the stray interwinding capacitance. They were probably constant-resistance coils in disguise. Capacitance to ground of the coil body is always a significant factor also.

Interstage Peaking

The Tektronix L and K units of the '50s were good examples of interstage T-coil peaking. The T-coils were used to peak, not the preamp input or the output, but in the middle of the amplifier. The interstage bandwidth was boosted well above the

$$f_{\text{interstage}} = \frac{1}{2\pi R_L C_{total}} = \frac{g_m}{gain\ 2\pi C_{total}} < \frac{g_m}{gain\ 2\pi C_{subtotal}} = \frac{f_r}{gain}$$

The individual pre-amp bandwidths are 60MHz. This is amazing because the effective f_t of the tubes was only 200MHz or so. Both inductive peaking and f_t doubling techniques were needed to "hot rod" these plug-ins to this bandwidth.

T-Coils in Transistor Interstages

The 150MHz 454 evolved from the 50MHz 453 oscilloscope by adding distributed deflection plates to the cathode ray tube and, among other things, using a new output amplifier. This amplifier employed T-coil peaking in the interstages. The T-coil design was based on a lossless virtual capacitance, a very big approximation. This virtual capacitance at the base was dominated by the transformation of the emitter feedback admittance into the base. The emitter feedback cascode connection made two transistors function more like a pentode. The initial use of transistors in the early '60s showed us that, most of the time, vacuum tube techniques didn't work with "those blasted transistors." After all, vacuum tubes had a physical capacitance that was measurable on an "off" tube; transistors had this "virtual capacitance thing"! The conventional thinking in the design groups at Tek in the early and mid '60s was that inductive peaking and transistor high-fidelity pulse amplifiers were not compatible. Despite this, the T-coils and transistors did work, the 454 worked, and the 454 was a "cash cow" for Tektronix for several years. Since then, ICs have displaced discrete transistors and the 'scope bandwidths translated upwards, with and without T-coils. The fastest amplifiers, however, are always produced with the aid of some T-coil configuration.

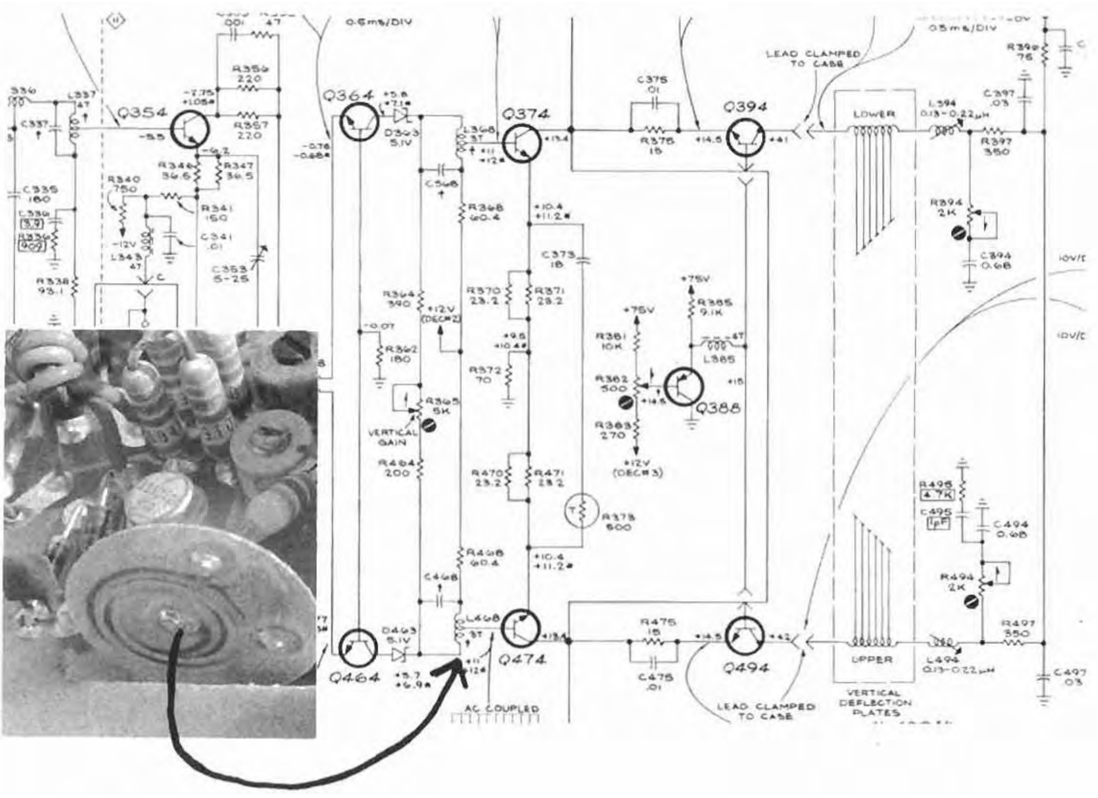

Figure 10–9. Tektronix 454 Vertical-Output Amplifier and Interstage T-coil.

Phase Compensation with T-Coils

The portable 453 needed a compact delay line for the vertical system that didn't require tuning. Kobbe had designed and developed a balanced-counterwound delay line for the 580 series of 'scopes. We made it still smaller. This delay line worked well at 50MHz, and had reasonably low loss at 150MHz. Unfortunately, the step response revealed a preshoot problem. The explanation in the frequency domain is nonlinear phase response. High-frequency delay was insufficient, and one could see it as preshoot in the step response. Three sections of a constant-resistance-balanced T-coil structure added enough high-frequency delay to clean up the preshoot, and even speed the risetime by moving high frequencies into their "proper time slot." T-coil sections can provide delay boost at high frequencies if the T-coil section is proportioned differently from that of the peaking application. A negative value for "k" is usually appropriate and is realized by adding a separate inductor in the common leg.

Integrated Circuits

In the late '60s, when the 454A was being developed, George Wilson, head of the new Tektronix Integrated Circuits Group at that time, wanted to promote the design of an integrated circuit vertical amplifier. I rebuffed him, saying, "We can never use ICs in vertical amplifiers because they have too much substrate capacitance, too much collector resistance, and too low an f_t." I was correct at the time, but dead wrong in the long run. In the '70s, Tektronix pushed IC development in parallel with the high-bandwidth 7000 series oscilloscopes.

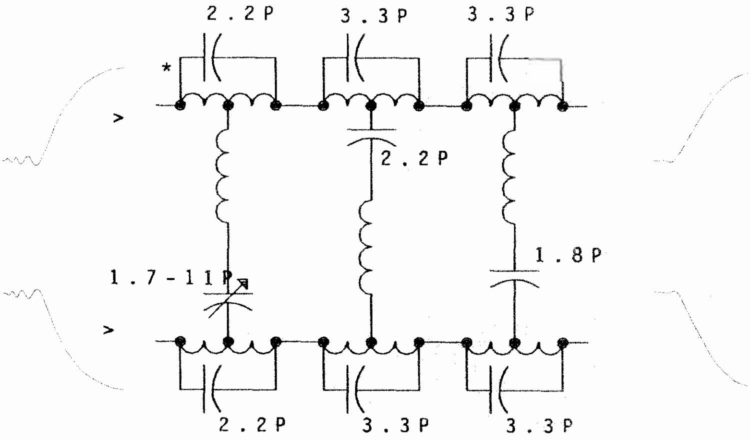

Figure 10–10. Correcting Insufficient High-Frequency Delay.

I stopped my slide into obsolescence in 1971 by doing a little downward mobility. I left the small portable oscilloscope group I headed, and joined George Wilson in the IC group as a designer. This foresight on my part was most uncharacteristic.

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T-Coils with Integrated Circuit Vertical Amplifiers

The initial use of integrated circuits in the vertical amplifiers of Tektronix 'scopes supplied a huge bandwidth boost, but not just because of the high f_t. New processes included thin film resistors that allowed designers to put the small value emitter feedback resistors on the chip, thus eliminating the connection inductance in the emitters of transistors. That emitter inductance had made a brick wall limit in bandwidth for discrete transistor amplifiers. That wall was pretty steep, starting in the 150–200MHz area. In order to have flat, non ripple, frequency response at VHF and UHF, the separately packaged vertical amplifier stages needed to operate in a terminated transmission line environment. T-coils were vital to achieve this environment. Thor Hallen derived formulas for a minimum VSWR T-coil. Packaging and bond wire layout made constant-resistance T-coil design impossible. Hallen's T-coil incorporated and enhanced the base connection inductance. The Tektronix 7904 achieved 500MHz bandwidth by using all of the above, along with 3GHz transistors and an ft-doubler amplifier circuit configuration.

In 1979, the 1GHz 7104 employed many of the 7904 techniques but, in addition, had 8GHz f_t transistors, thin film conductors on substrates, and a package design having transmission line interconnects. It also had a much more sensitive cathode ray tube. Robert Ross had earlier developed formulas for a constant-resistance T-coil to drive a non-pure capacitor (a series capacitor-resistance combination). John Addis and Winthrop Gross made use of the Ross type T-coils (patterned with the thin film conductor) to successfully peak the stages and terminate the inter-chip transmission lines.

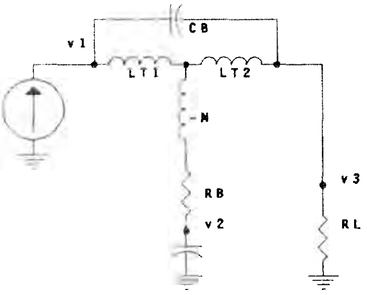
I have lumped Thor Hallen's and Bob Ross's T-coils together in a class I call "lossy capacitor T-coils."

Dual Channel Hybrid with T-Coils

In 1988, the digitizing 1GHz Tektronix 11402 was introduced. A fast real-time cathode ray tube deflection amplifier was no longer needed. T-coils were employed, however, in the 11A72 dual-channel plug-in preamp hybrid (Figure 10–12), where all of the two-channel analog signal processing took place. The T-coils peaked frequency response and minimized input reflections in the 50 Ohm input system. As in the 7904 'scope, Hallen used a design technique for the T-coils that minimized VSWR. To realize this schematic, a T-coil was needed which had

Two Types of Lossy Capacitor T-coils

ROSS CONSTANT-RESISTANCE T-COIL



$$L_{T1}=\frac{R_L^2C}{2}(1-\frac{R_B}{R_L})$$

$$L_{T2}=\frac{R_L^2C}{2}(1+\frac{R_B}{R_L})$$

$$C_B=\frac{C}{16\delta^2}(1+\frac{R_B}{R_L})^2$$

$$M=\frac{R_L^2C}{4}[1-(\frac{R_B}{R_L})^2-\frac{1}{4\delta^2}(1+\frac{R_B}{R_L})^2]$$

$\delta = \mathit{damping factor}$ of quadratic response

$\frac{v1}{i}=R_L$ The Constant-Resistance property

$$\frac{v2}{iin}=\frac{R_L}{1+\frac{(R_L+R_B)}{2}Cs+R_L^2CC_Bs^2}$$

Two Pole Response

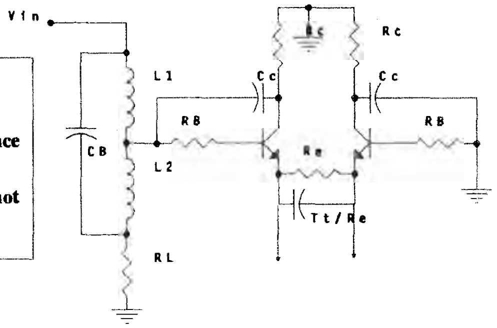
HALLEN MINIMUM VSWR T-COIL

For the Hallen and the Ross T-coils

$L_{\text{total}}=R_L^2C_{\text{total}}$

As R_B gets bigger, the input coil inductance gets smaller.

With a finite R_B, the response at R_L is not allpass



$$L_{total}=R_L^2[\frac{T_T}{R_e}+(\frac{R_c}{R_e}+1)\,C_c]$$

$$L_1=\frac{L_{total}}{2}[1+\frac{1}{R_L}(\frac{R_eC_cT_t(R_c+2R_B)}{(T_t+R_eC_c+R_cC_c)^2}-\frac{2R_BT_t+R_eR_cC_c}{T_t+R_eC_c+R_cC_c})]$$

$$L_2=L_{total}-L_1$$

$$C_B=\frac{1}{R_L^2}[\frac{R_LC_cT_t(R_c+2R_B)(L_1-L_2)}{(T_t+R_eC_c+R_cC_c)(L_1+L_2)}+\frac{2R_BR_cC_cT_t}{T_t+R_eC_c+R_cC_c}+\frac{L_1L_2}{L_1+L_2}]$$

Figure 10–11.
Two Types of Lossy Capacitor T-coils.

enough mutual inductance to cancel the bond wire inductance that would be in series with its center tap. The remaining net branch inductances then had to match Hallen's values. To guide the physical layout of this coil, I used a three-dimensional inductance calculation program. This program was used iteratively. The two "G" patterns on the multilayer thick film hybrid are the top layer of these input T-coils. The major dimension of these coils is 0.05 inches. In between the chips are coils which "tune out" the collector capacitance of the transistor of each output channel. These coils are formed by multiple-layer runs and bond wire "loopbacks."

Afterglow

Conspicuous by its absence is a discussion of wideband amplifier configurations and how they operate. I have referred to f_t-doublers and current doublers without explanation. I had to really restrain myself to avoid that topic for the sake of brevity. The ultimate bandwidth limit of high-fidelity pulse amplifiers depends on the power gain capability (expressed by an f_{MAX}, for example) of the devices, and the power gain requirements of the amplifier. To approach this ultimate goal requires the sophisticated use of inductors to shape the response. For bipolar transistors, the f_t-doubler configurations and single-stage feedback amplifiers, combined with inductive peaking, do a very good job.

I hope this chapter has raised your curiosity about the circuit applications of the T-coil section. I have not written this chapter like a textbook

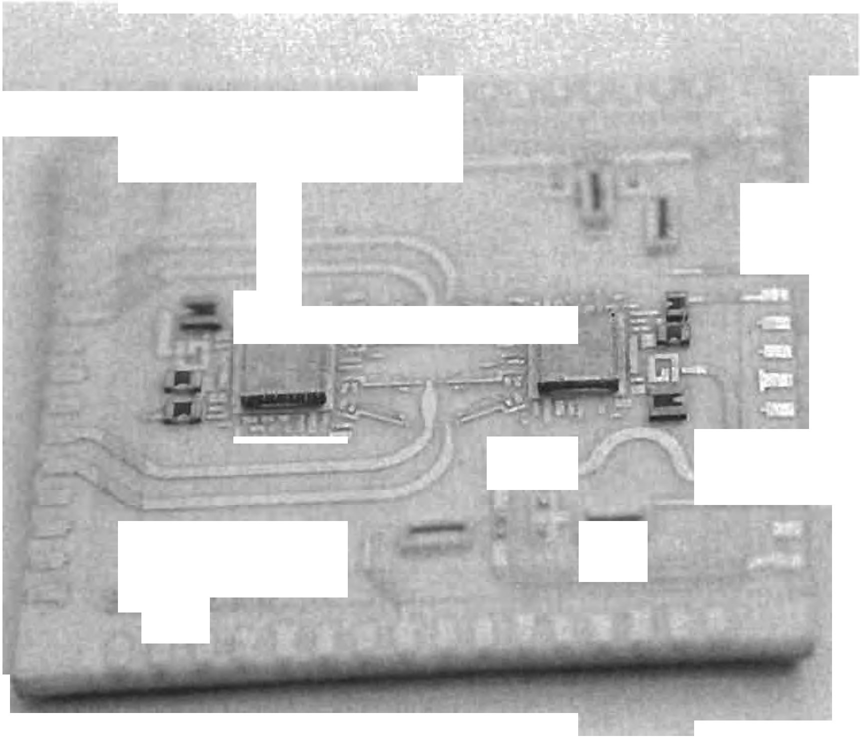


Figure 10–12. 11A72 1.5GHz Multilayer Hybrid with Thick Film T-coils.

and I am hoping that my assertions and derivation results are challenged by the reader. To get really radical, breadboard a real circuit! A less fun but easier way to verify circuit behavior is via SPICE or a similar simulator program. Keep in mind, while you are doing this, that most of the very early design took place without digital computer simulators. Frequency- and impedance-scaled simulations took place though, with physical analog models.

I'm grateful to the many knowledgeable folks who talked with me recently and added considerable information, both technical and historical. These included Gene Andrews, Phil Crosby, Logan Belleville, Dean Kidd, John Kobbe, Jim Lamb, Cliff Moulton, Oscar Olson, Ron Olson, and Richard Rhiger. If this chapter has errors, however, don't blame these guys; any mistakes are my own.

Bob Ross and Thor Hallen have been sources of insight on these topics over many years and have been ruthless in their rigorous analyses, helping me in my work immensely.

Finally, I leave you with my mother's and Socrates' advice, "Moderation in all things." Might I add, "Just do it!" If these Tek guys had waited for proper models of all known effects and proper theory before doing something, we would still be waiting. Everything can be tidied up in hindsight but, in fact, the real circuits in the real products are often more complicated than our simple schematics and were realized by a lot of theory, intuition, and especially smart, hard, and sometimes long work. I am proud of all of this heritage and the small part I played in it.