

T-Coil Topics

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Topics and Goals

- Old technology, current applications
 - Historical overview
 - Some recent applications
 - Some extensions
- Introduce standard T-coils and features
- Partially introduced in IBIS Summit, Beijing, 2007 as part of a Wang Algebra presentation
- Relates to IBIS and IBIS-AMI and IBIS-ISS
 - Some Recent SerDes design methods use T-coils
 - SPICE subcircuit, Laplace transform, S-parameter representations

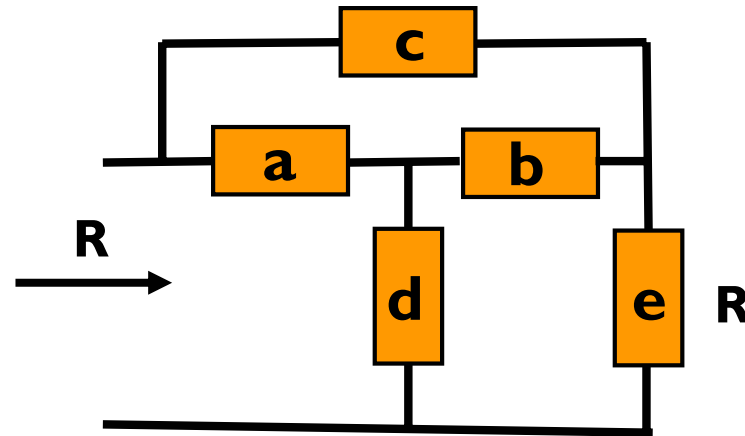


Bridged T-coil Properties

- T-coil summary
 - Constant R provides ideal load or termination
 - Up to 2.82 bandwidth improvement (BWVER or bandwidth extension ratio) over RC based bandwidth
 - 2.73 improvement for acceptable 0.4% overshoot to ideal step input (MFED or maximally flat envelope delay design)
 - Complexity reduction (poles/zero cancellation)
- Now used in high-speed buffer design
 - ESD (electrostatic discharge) compensation
 - Bandwidth improvement



Constant R Constraint



General

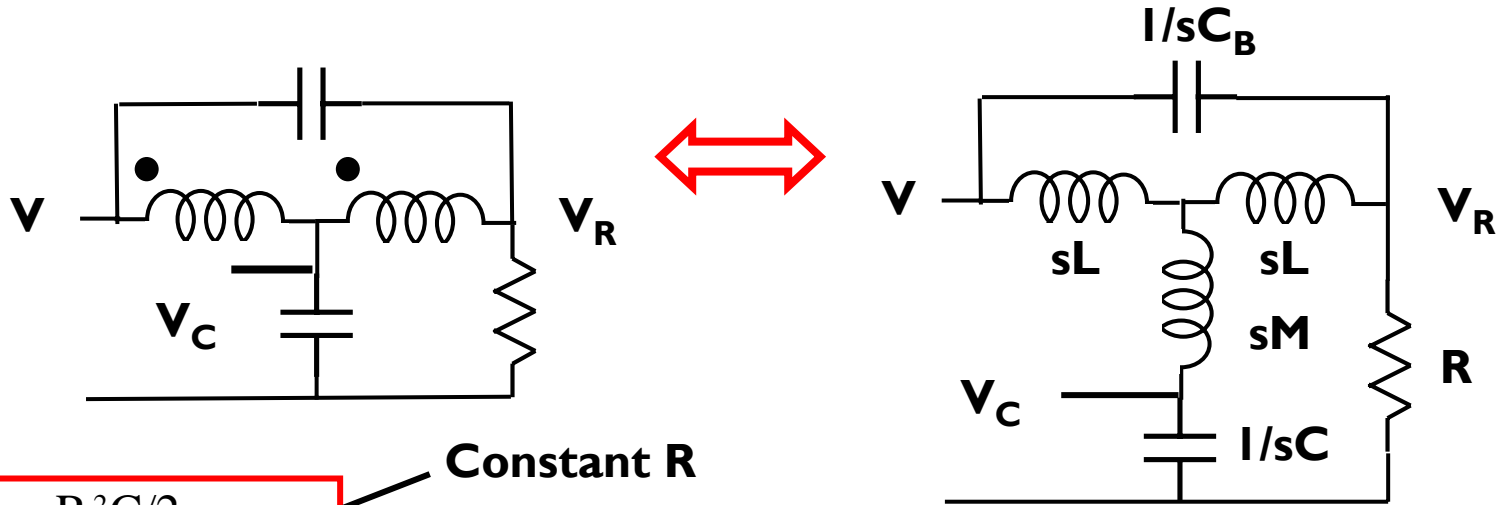
$$d(a + b) + ab + R(a - b) - R^2 - \frac{R^2(a + b)}{c} = 0$$

Symmetric (a = b)

$$2da + a^2 - R^2 - \frac{2R^2a}{c} = 0$$

Substitute impedances and equate powers of the Laplace variable “s” for constant R relationships

(Constant R) Bridged T-coil Example



Constant R

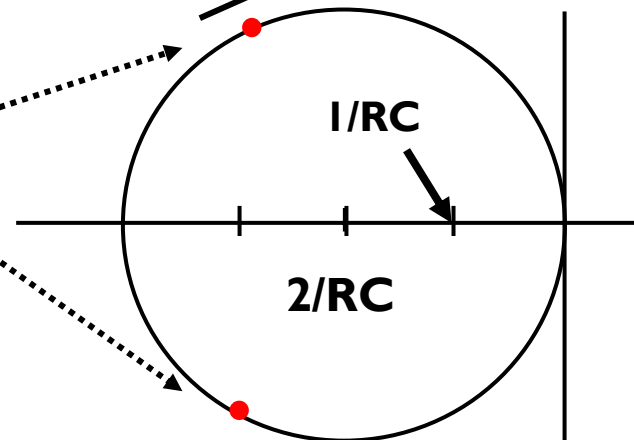
$$L = R^2 C / 2$$

$$M = R^2 C_B - L / 2$$

$$\frac{V_C}{V} = \frac{1}{R^2 C C_B s^2 + \frac{RC}{2} s + 1}$$

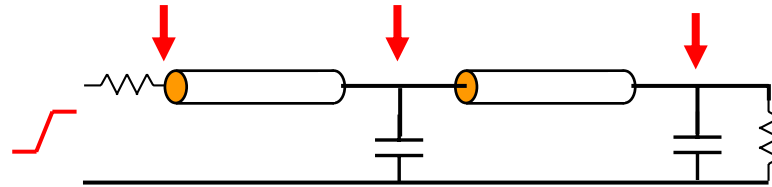
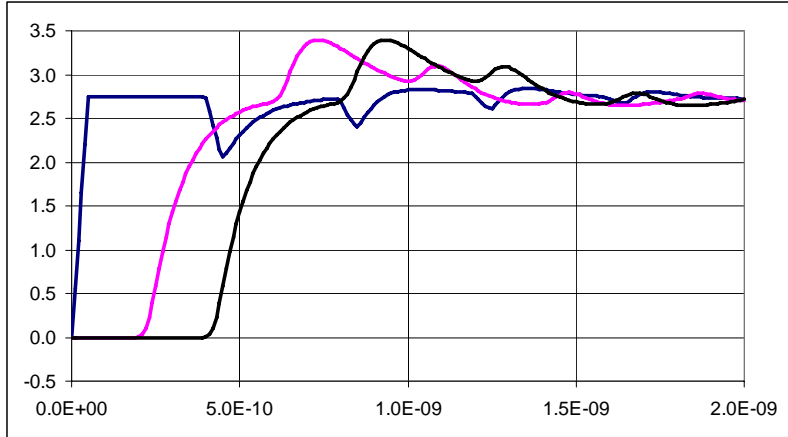
$$\frac{V_R}{V} = \frac{R^2 C C_B s^2 - \frac{RC}{2} s + 1}{R^2 C C_B s^2 + \frac{RC}{2} s + 1}$$

Increasing C_B



Poles 30 degrees for maximally flat envelope delay (MFED)

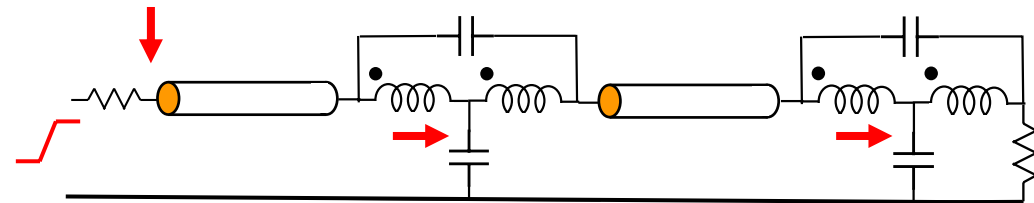
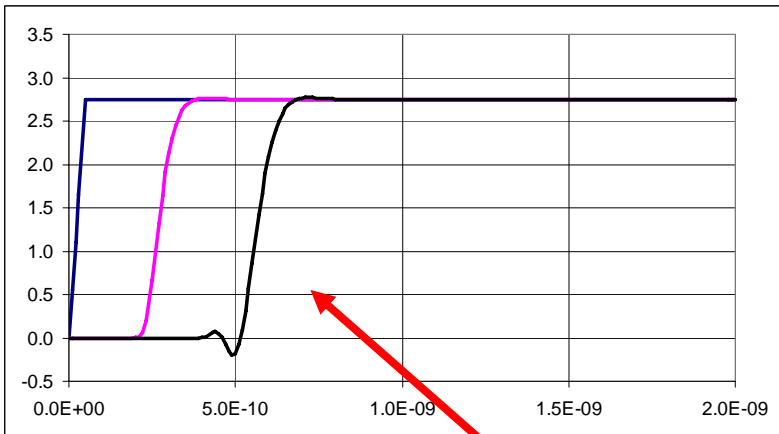
T-coil Improvement (terminated multi-drop Line)



$R_{source} = 10 \Omega$, $R_{load} = 50 \Omega$

$C = 2 \text{ pF}$, $TL = 50 \Omega$, 200 ps

$V_{in} = 0 \text{ to } 3.3 \text{ V}$, 50 ps ramp



Cleaner and faster responses, but with more delay

Historical Applications (I)

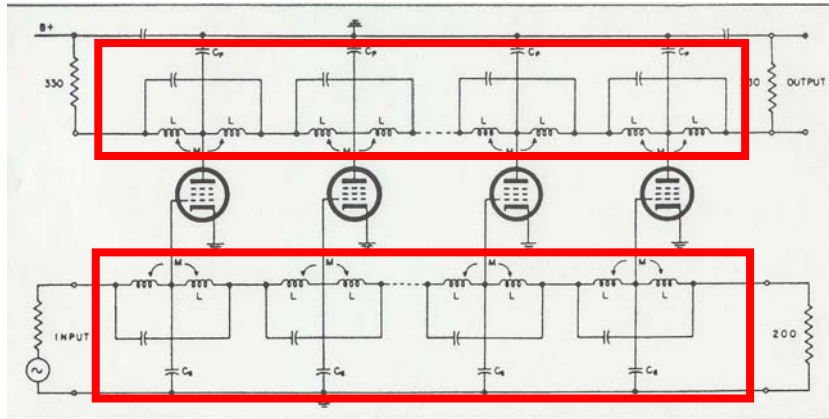
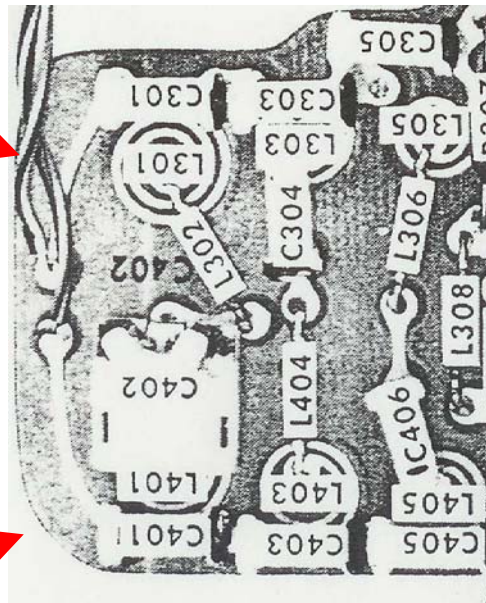
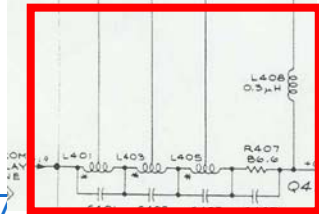
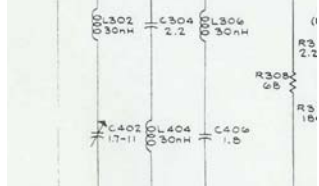
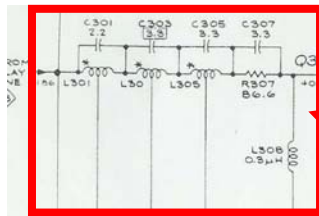


Figure 3. Basic Amplifier Circuit Using Bridged-T Lines

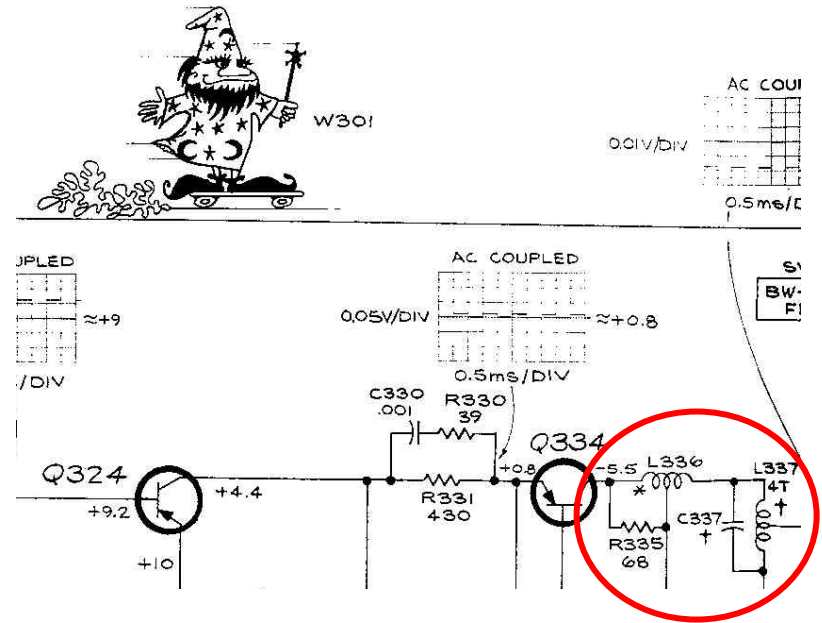
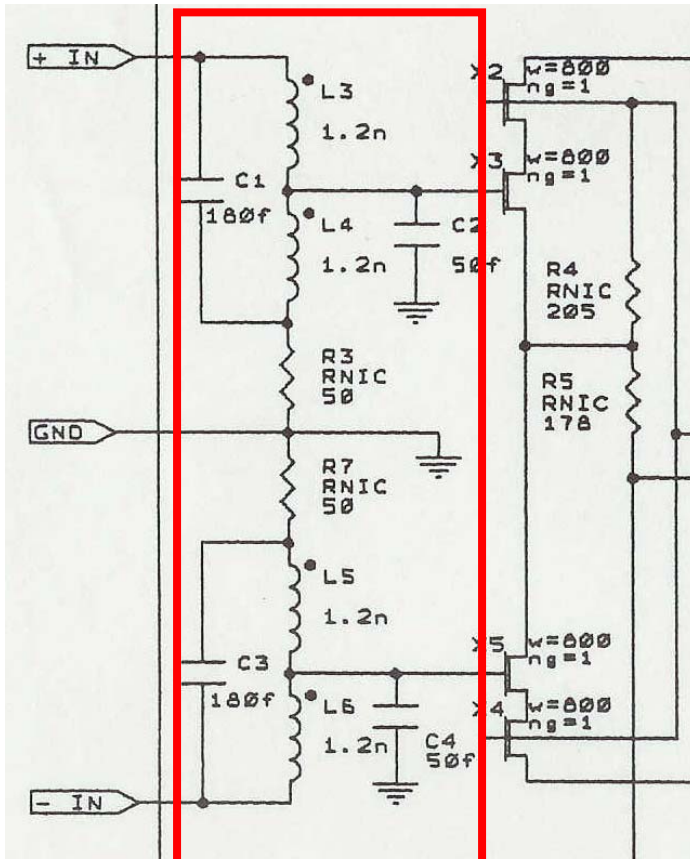
High speed (traveling wave) distributed amplifier in 1940's (Similar to GTL and source synchronous control)



Dual input delay line phase equalization using cascaded printed circuit board T-coils in 1960's

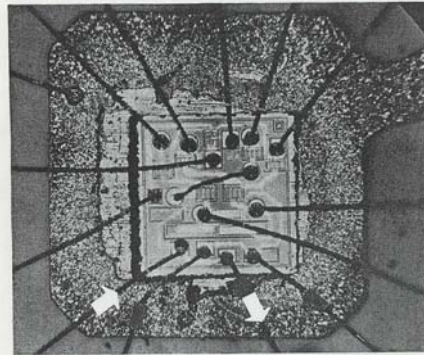
Historical Applications (2)

High speed 50 Ω input for FET hybrid IC and with metalization (not shown) for T-coils in 1990's



Parasitic bandwidth limit
switch compensation and
interstage peaking in 1960's
(and W301)

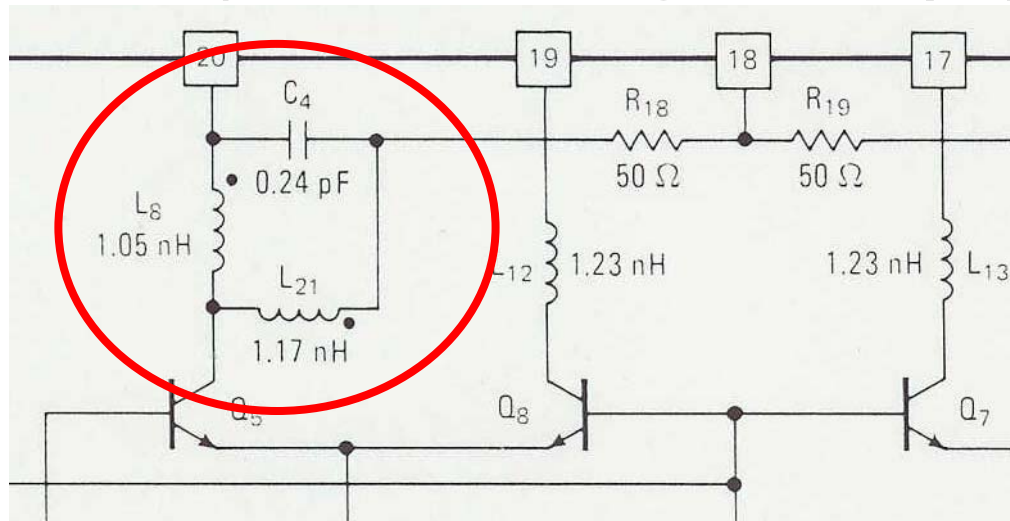
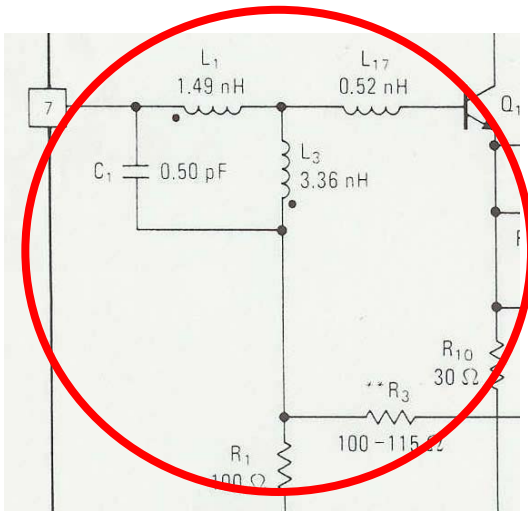
Historical Applications (3)



7. A chip trick. Tee-coil is realized by looping the input signals thrc

Package bond wire compensation with T-coil trick in 1970's

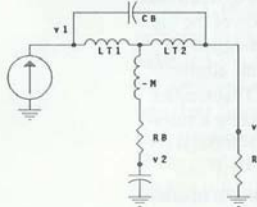
One-half of hybrid IC differential 50 Ω input and 50 Ω output with asymmetrical T-coils in 1970's (Current mode logic-like output)



Early Asymmetrical Lossy T-coils

Two Types of Lossy Capacitor T-coils

ROSS CONSTANT-RESISTANCE T-COIL



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

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

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

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

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

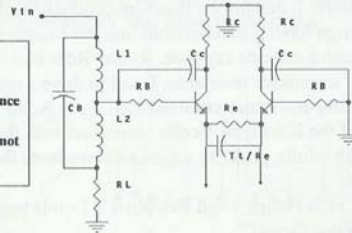
$\frac{v1}{i} = R_L$ The Constant-Resistance property

$$\frac{v2}{i_{in}} = \frac{R_L}{1 + \frac{(R_L + R_B)}{2} C s + R_L^2 C C_B s^2}$$

Two Pole Response

HALLEN MINIMUM VSWR T-COIL

For the Hallen and the Ross T-coils
 $L_{total} = R_L^2 C_{total}$
 As R_B gets bigger, the input coil inductance gets smaller.
 With a finite R_B , the response at R_L is not allpass

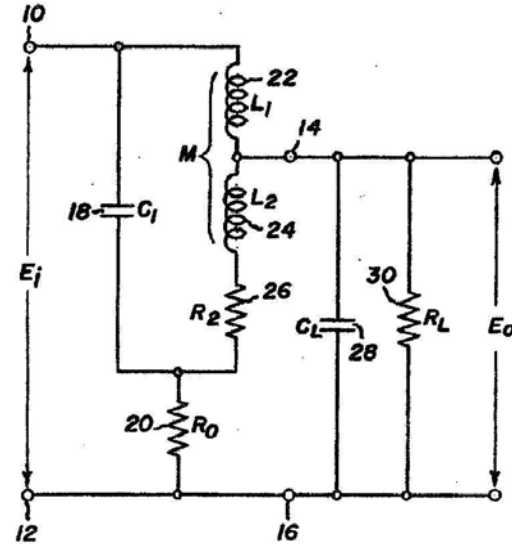


$$L_{total} = R_L^2 \left[\frac{T_T}{R_e} + (R_e + 1) C_c \right]$$

$$L_1 = \frac{L_{total}}{2} \left[1 + \frac{1}{R_L} \left(\frac{R_e C_c T_i (R_e + 2R_B)}{(T_i + R_e C_c + R_c C_c)^2} - \frac{2R_B T_i + R_e R_c C_c}{T_i + R_e C_c + R_c C_c} \right) \right]$$

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

$$C_B = \frac{1}{R_L^2} \left[\frac{R_L C_c T_i (R_e + 2R_B) (L_1 - L_2)}{(T_i + R_e C_c + R_c C_c) (L_1 + L_2)} + \frac{2R_B R_c C_c T_i}{T_i + R_e C_c + R_c C_c} + \frac{L_1 L_2}{L_1 + L_2} \right]$$



T. T. True patent
(1964)

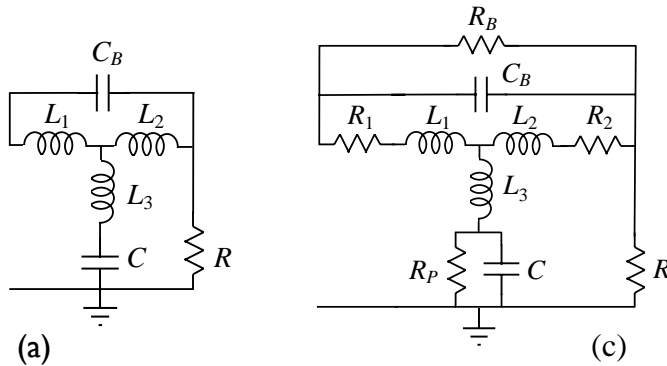
Tuned for bipolar
transistor technology



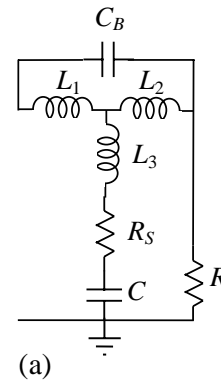
Figure 10-11.
Two Types of Lossy
Capacitor T-coils.

Constant Input-R, 2nd Order Extensions

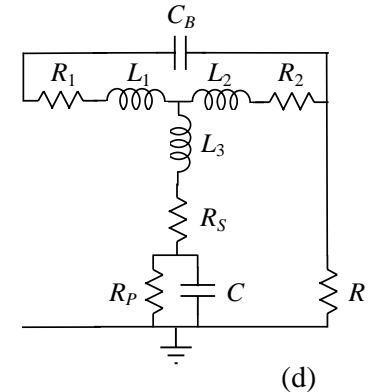
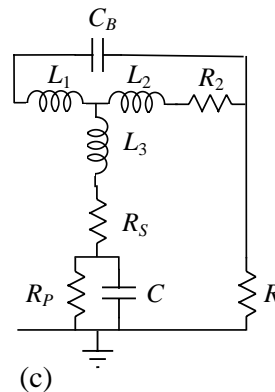
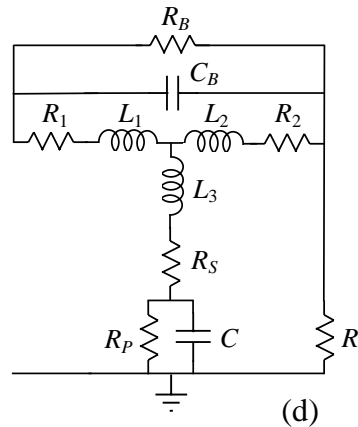
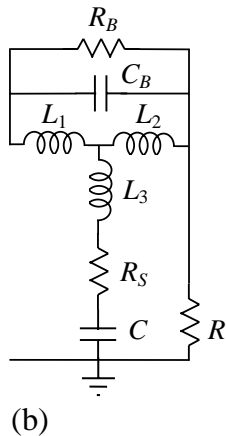
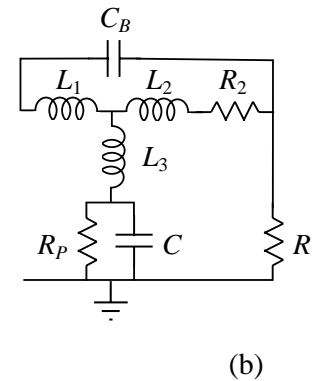
Standard



Series Rs



T.T. True



General

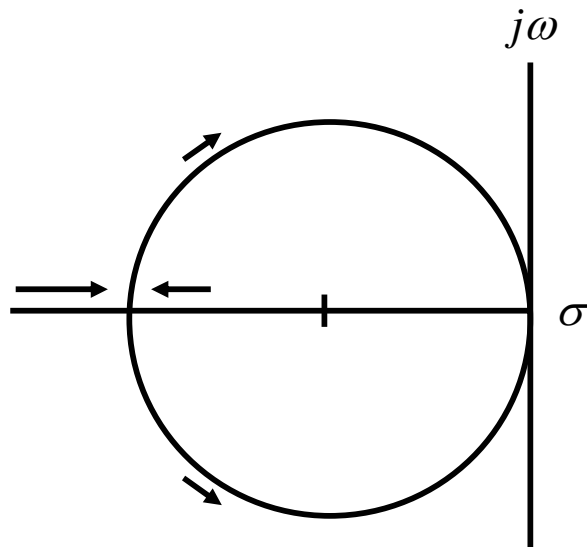
General

Fig. 1
Symmetrical ($Z_1=Z_2$),
 R_B added

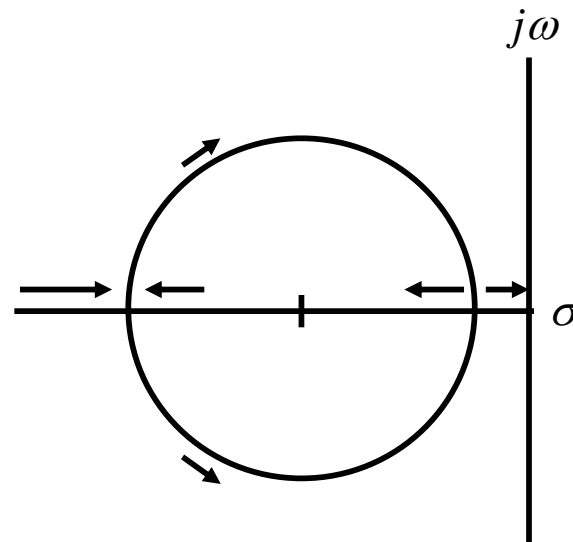
Fig. 2
Asymmetrical
($Z_1 \neq Z_2$)



2nd Order Root Loci for Increasing C_B : (a) without R_p , $D_1=0$ (b) with R_p



(a)



(b)

$$\frac{V_C}{V} = \frac{1}{B_0 + B_1s + B_2s^2} = \frac{1}{B_0 + (D_0 + D_1C_B)s + D_2C_Bs^2}$$

$$\text{center} = -\frac{B_0}{D_0}, \quad \text{radius} = \frac{B_0}{D_0} \sqrt{1 - \frac{D_0D_1}{B_0D_2}}$$



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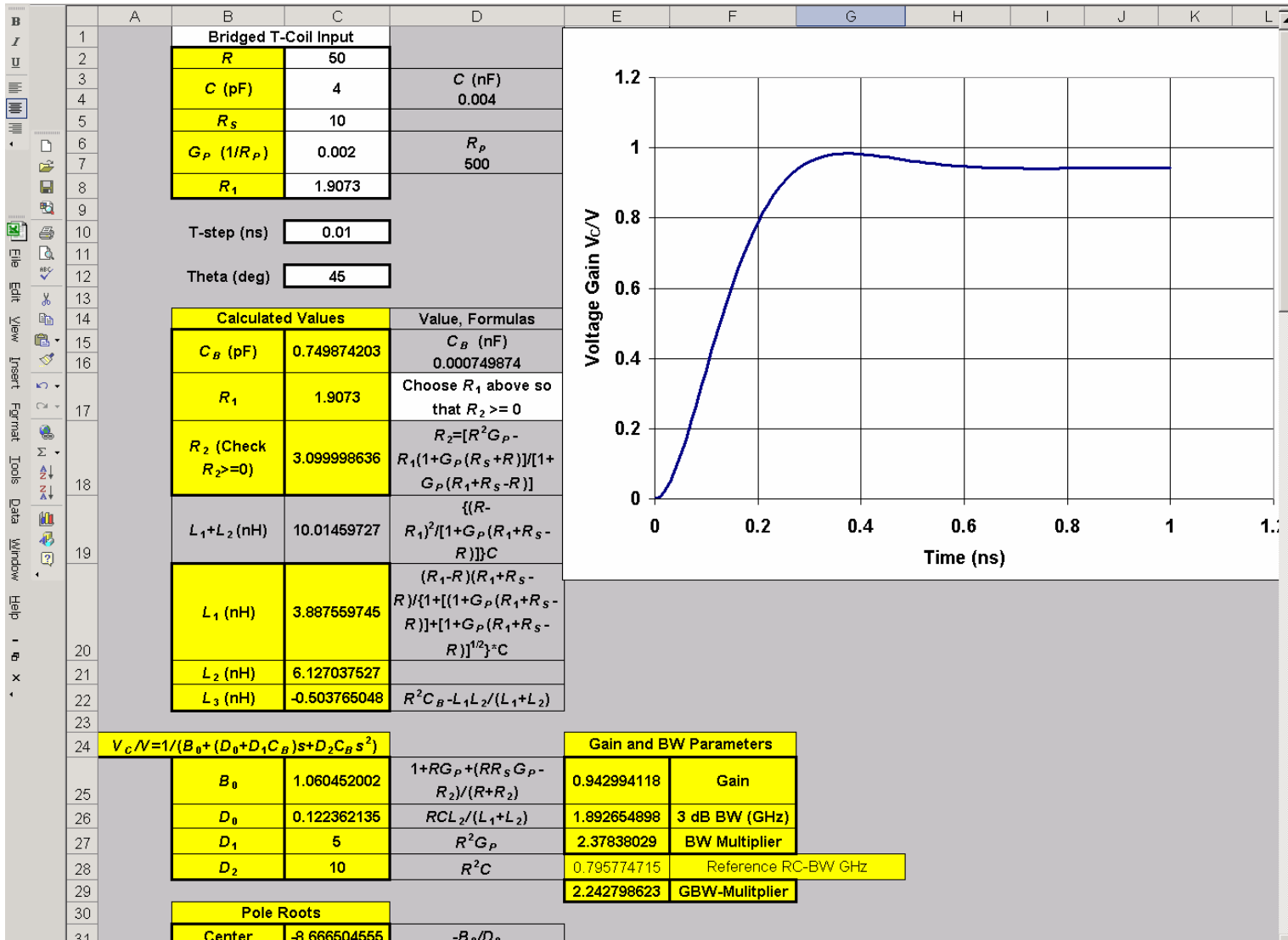
Examples for all Extensions

$R = 50 \Omega$, $C = 4 \text{ pF}$, $R_S = 10 \Omega$, $R_P = 500 \Omega$, Pole Angle = 30° & 45° , R_1 selected for Fig. 2(d)

Load Fig.	Symmetrical T-Coils				Asymmetrical T-Coils			
	Standard C 1(a)	R_S - C 1(b)	R_P C 1(c)	R_S - R_P C 1(d)	R_S - C 2(a)	R_P C 2(b)	R_S - R_P C 2(c)	Gen. R_S - R_P C 2(d)
R_1			2.5 Ω	2.5 Ω				1.907 Ω
R_2			2.5 Ω	2.5 Ω		5.556 Ω	5.435 Ω	3.100 Ω
R_B		250 Ω	2000 Ω	222.2 Ω				
L_1	5 nH	5 nH	5.025 nH	5.025 nH	4 nH	5.409 nH	4.257 nH	3.888 nH
L_2	5 nH	5 nH	5.025 nH	5.025 nH	6 nH	5.702 nH	6.612 nH	6.127 nH
Gain	1	1	0.95	0.95	1	1	0.98	0.943
C_B (30°)	0.333 pF	0.653 pF	0.362 pF	0.698 pF	0.480 pF	0.364 pF	0.504 pF	0.489 pF
L_3	(-1.667 nH)	(-0.867 nH)	(-1.609 nH)	(-0.767 nH)	(-1.200 nH)	(-1.867 nH)	(-1.330 nH)	(-1.154 nH)
BW	2.167 GHz	1.548 GHz	2.136 GHz	1.536 GHz	1.806 GHz	2.075 GHz	1.780 GHz	1.841 GHz
BWER	2.723	1.945	2.684	1.930	2.269	2.607	2.237	2.314
GBWER	2.723	1.945	2.550	1.834	2.269	2.607	2.193	2.182
C_B (45°)	0.500 pF	0.980 pF	0.552 pF	1.074 pF	0.720 pF	0.556 pF	0.772 pF	0.750 pF
L_3	(-1.250 nH)	(-0.050 nH)	(-1.133 nH)	0.173 nH	(-0.600 nH)	(-1.387 nH)	(-0.659 nH)	(-0.504 nH)
BW	2.251 GHz	1.608 GHz	2.198 GHz	1.575 GHz	1.876 GHz	2.135 GHz	1.829 GHz	1.893 GHz
BWER	2.828	2.020	2.763	1.980	2.357	2.683	2.298	2.378
GBWER	2.828	2.020	2.625	1.881	2.357	2.683	2.253	2.243



General Asymmetrical Calculations



Parameterized SPICE Automatic T-coil Design Subcircuit

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*****
*ASYMMETRICAL T-COIL WITH PARAMETERS
*****

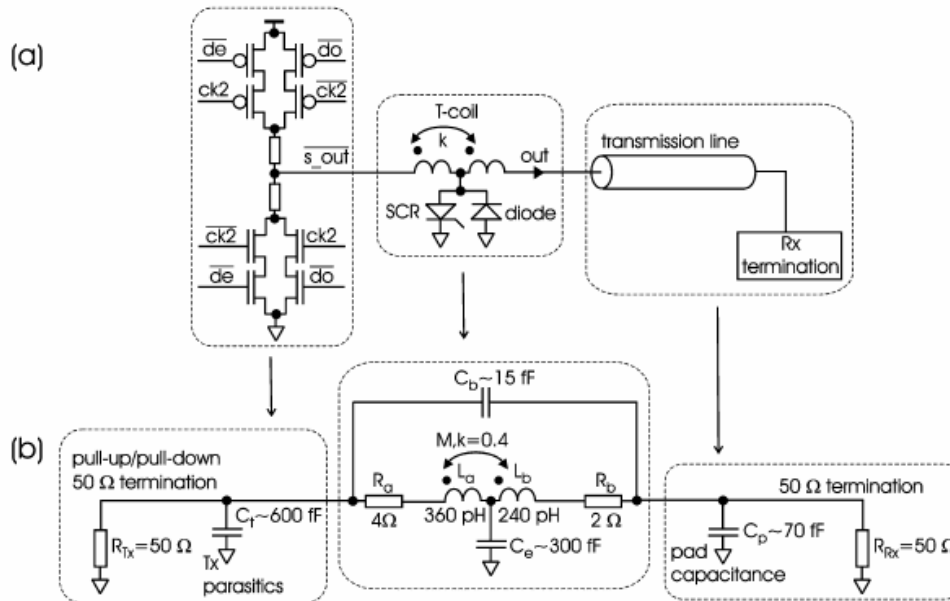
*****
* PARAMETERS
*****
** ENTER
.param R = 50                $ Load Resistor
.param C = 4e-12             $ Load Capacitance
.param RS = 10 $ set 'max(1e-10, 10)' $ Series Resistor
.param RP = 500 $ set 'max(1e-10, 500)' $ Parallel Resistor
.param CB = 0.653p
.param R1 = 2 $ set 'max(1e-10, 2)' $ Select R1 with RP>0
** CALCULATED
.param GP = '1/RP'          $ Parallel Conductance
.param R2 = 'max(1e-10, (R*R*GP-R1*(1+(RS+R)*GP))/(1+(R1+RS-R)*GP))'
.param LT = '(R-R1)*(R-R1)*C/(1+(R1+RS-R)*GP)'
.param L1 = '(R1-R)*(R1+RS-R)*C/(1+(R1+RS-R)*GP+SQRT(1+(R1+RS-R)*GP))'
.param L2 = 'LT-L1'
.param L3 = 'R*R*CB-L1*L2/(L1+L2)'
*
*****
* ASYMMETRICAL T-COIL CIRCUIT (Ground = 0)
*****
*
XCOIL1 in outc outr TCOIL_ASM
RLOAD 0 outr R='R'
*
*****
* SUBCKT: TCOIL_CONSTANT RESISTANCE T-COIL (RL)
*****
.SUBCKT TCOIL_ASM in outc outr
*
L1 1 d L='L1'
L2 2 d L='L2'
R1 in 1 R='R1'
R2 outc 2 R='R2'
CB in outr C='CB'
*
L3 d 3 L='L3' $ Negative L3 ok
RS 3 outc R='RS'
C outc 0 C='C'
RP outc 0 R='RP'
.ENDS
*
*****
```

More Recent Work in Last 10 Years (dozens of contributions)

- Technical literature (journals, conferences, thesis, and patents) for up to 40 Gb/s designs
- T-coil types
 - Standard
 - Extended – multiple higher order with/without bridging capacitance
 - Sometimes with other C's and losses
- Part of high speed designs
 - ESD compensation
 - Acceptable (but not 0) S11 and extended (>4) S21 bandwidths
 - Up to 5th order to polynomials fitted by (Bessel coefficients, optimization or approximation equations)
- Inductance structure contributions
- Splitting the C load strategies for better performance



Example of a Recent IC T-Coil Application



Low S11 with a forth order polynomial extension and lossy fabrication for ESD compensation

M. Kossel, C. Menolfi, J. Weiss, P. Buchmann, G. von Bueren, L. Rodoni, T. Morf, T. Torifl, and M. Schmalz, “A T-Coil-Enhanced 8.5 Gb/s High Swing SST Transmitter in 65 nm Bulk CMOS With < -16 dB Return Loss Over 10 GHz Bandwidth,” IEEE J. Solid-State Circuits, Dec. 2008

Summary

- Some T-coil background and history
- Second order extensions for lossy design applications
 - Due to more detailed load models
 - Due to inductor fabrication losses
 - Parameterized by C_B for greater solution space versus often used inductor coupling coefficient
 - Used in current IC buffer design including SerDes
- T-coils can be a factor in IBIS-AMI and IBIS-ISS applications