Topics in IC Design

T-Coil

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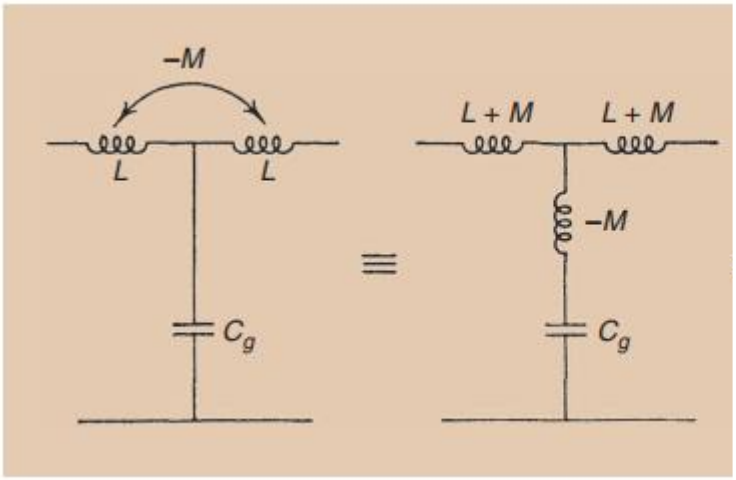
(Compliment to Hyungrok Do)

Introduction

- **Inductors produce peaking, thereby giving bandwidth extension.**
- **T-coil (Tee-Coil) produces even more bandwidth extension by giving negative inductance.**



Dot convention

Same direction : k > 0

Opposite direction : k < 0

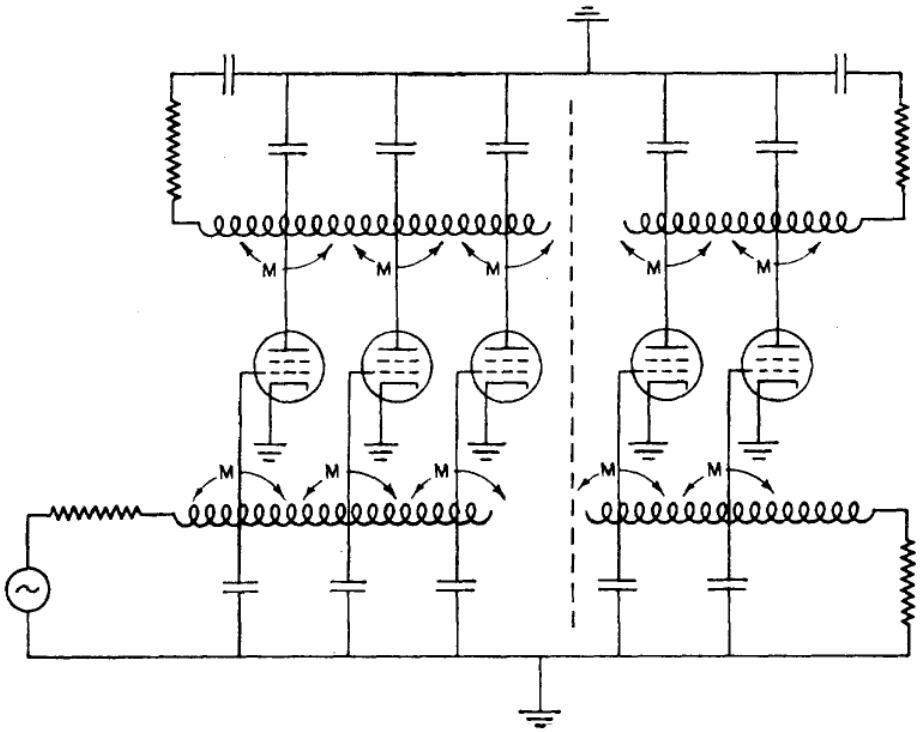
$$\mathbf{M = k\sqrt{L_1 L_2}}$$

|k| ≤ 1

|k| = 1 when inductors share all of their magnetic flux.

Introduction

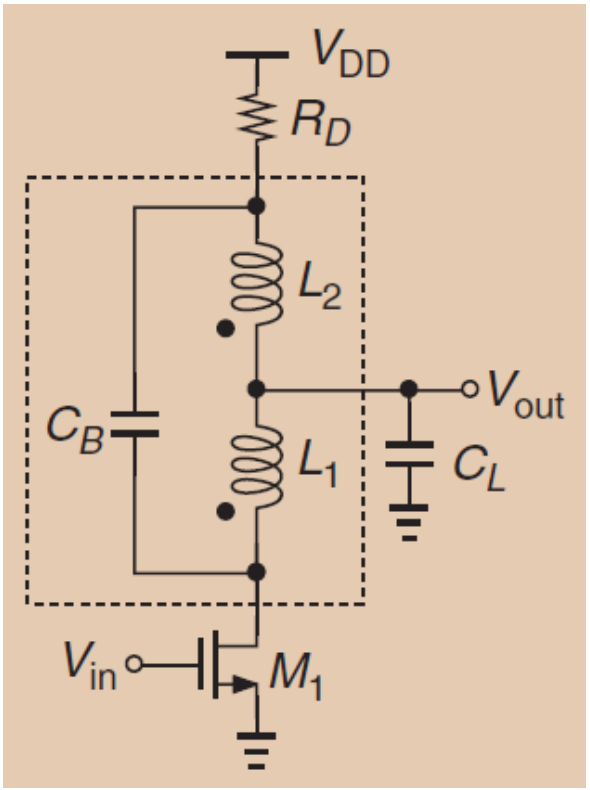
- **Introduced by Ginzton in 1948 as part of distributed amplifier.**



[0] Ginzton, Proc IRE, 1948

T-Coil

- **Common Source Amplifier**



Without T-Coil,

$$\frac{V_{out}}{V_{in}}(s) = -g_m R_D \frac{1}{1 + sR_D C_L}$$

$$\boldsymbol{f_{3dB} = 1/2\pi R_D C_L}$$

With T-Coil,

$$\frac{V_{out}}{V_{in}}(s) = -g_m R_D \frac{a_2 s^2 + a_1 s + 1}{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + 1}$$

where

$$a_2 = (L_1 + L_2 + 2M) C_B$$
$$a_1 = (L_2 + M)/R_D$$
$$b_4 = C_B C_L (L_1 L_2 - M^2)$$
$$b_3 = C_B C_L R_D (L_1 + L_2 + 2M)$$
$$b_2 = C_B (L_1 + L_2 + 2M) + C_L L_2$$
$$b_1 = R_D C_L.$$

[1] B. Razavi, ISSC Magazine, 2015

Symmetric T-Coil

- **When two zeros in the numerator are cancelled by two of the four poles in the denominator, the second-order transfer function is obtained.**

$$\frac{V_{\text{out}}}{V_{\text{in}}}(s) = -g_m R_D \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- ***Given R_D and C_L, what are C_B, L, and M, assuming $L_1 = L_2 = L$ (symmetric T-Coil)?***

$$b_4\omega_n^2 = a_2$$
$$b_3\omega_n^2 = a_2 2\zeta\omega_n + a_1$$
$$b_2\omega_n^2 = a_2\omega_n^2 + a_1 2\zeta\omega_n + 1$$
$$b_1\omega_n^2 = a_1\omega_n^2 + 2\zeta\omega_n$$

- ***Four equations must be satisfied with five variables (C_B, L, M, ζ, ω_n). Out of numerous solutions, what is the best transfer function that maximizes the bandwidth?***

Symmetric T-Coil

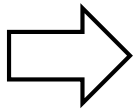
- **Let $k=M/L$ and simplify 4 equations.**

$$\frac{C_B}{C_L}=\frac{1}{4}\frac{1-k}{1+k}$$

$$\frac{k}{1+k}C_L=\frac{(1+k)L}{R_D^2}-2C_B$$

$$\omega_n^2=\frac{2}{(1-k)LC_L}$$

$$\zeta=\frac{R_DC_L-(1+k)L/R_D}{\sqrt{2(1-k)LC_L}}$$



$$L=\frac{R_D^2C_L}{4}\left(1+4\zeta^2\right)$$

$$k=\frac{4\zeta^2-1}{4\zeta^2+1}$$

$$C_B=\frac{C_L}{16\zeta^2}$$

$$\omega_n^2=\frac{16\zeta^2}{R_D^2C_L^2}$$

- **Then, determine ζ that maximizes the bw.**

[1] B. Razavi, ISSC Magazine, 2015

Symmetric T-Coil

- **With the following 2nd order transfer function,**

$$\frac{V_{\text{out}}}{V_{\text{in}}}(s) = -g_m R_D \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- **3-dB BW with T-Coil is**

$$\omega_{BW,T-Coil}^2 = \left[1 - 2\zeta^2 + \sqrt{\left(1-2\zeta^2\right)^2 + 1}\right]\omega_n^2$$

$$= \left[1 - 2\zeta^2 + \sqrt{\left(1-2\zeta^2\right)^2 + 1}\right]\frac{16\zeta^2}{R_D^2 C_L^2}$$

which is maximized when $\zeta = \sqrt{2}/2$**.**

- **Then**

$$\omega_{BW,T-Coil} = \omega_n = 2\sqrt{2}\,\frac{1}{R_D C_L}$$

$$= 2.828\omega_{3dB}$$

[1] B. Razavi, ISSC Magazine, 2015

Symmetric T-Coil

- **The maximum bandwidth solution is**

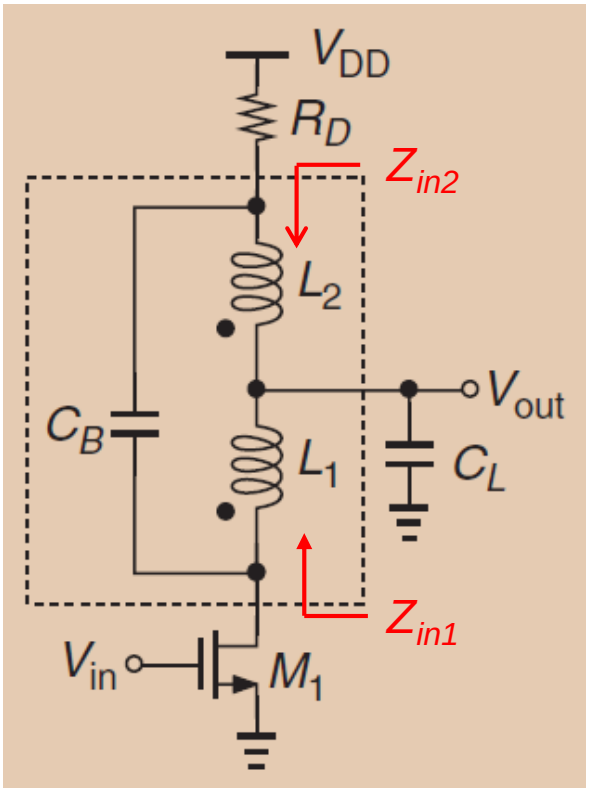
$$L = \frac{3}{8} R_D^2 C_L, M = \frac{1}{3} L, C_B = \frac{1}{8} C_L, \omega_n = 2\sqrt{2}/R_D C_L$$

which extends the bandwidth by 2.828.

BWER=2.828

Features of Symmetric T-Coil

- **What are its input impedances Z_{in1} and Z_{in2}?**



Under the maximum bandwidth condition,

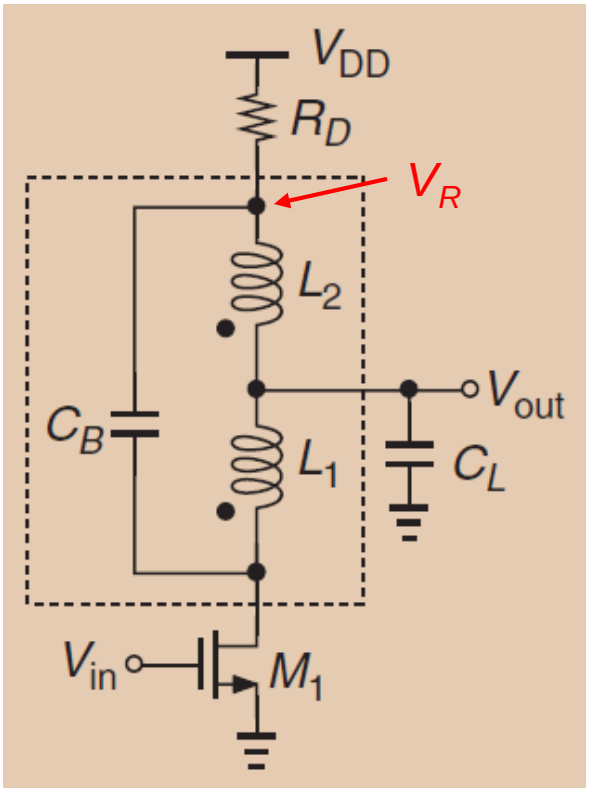
$$Z_{in1} = R_D$$

$$Z_{in2} = \infty$$

T-Coil is transparent.
C_L is not seen.
Can be used for return loss (RL) minimization.

Features of Symmetric T-Coil

- **What is the transfer function to the resistor node?**



- Under the maximum bandwidth condition,

$$\frac{V_R}{V_{in}}(s) = -g_m R_D \frac{s^2 - 2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- **All-pass function** with infinite bandwidth!

- Extra **phase delay** could be a problem.

$$\Delta\emptyset(\omega) = -2\arctan\left[\frac{2\zeta\omega_n\omega}{\omega_n^2 - \omega^2}\right]$$

Asymmetric T-Coil

- **With one less constraint ($L_1 \neq L_2$), more freedom for design is utilized to extend the bandwidth at the cost of higher design complexity.**
- ***Given R_D and C_L, what are C_B, L_1, L_2, and M?***

$$b_4\omega_n^2 = a_2$$
$$b_3\omega_n^2 = a_2 2\zeta\omega_n + a_1$$
$$b_2\omega_n^2 = a_2\omega_n^2 + a_1 2\zeta\omega_n + 1$$
$$b_1\omega_n^2 = a_1\omega_n^2 + 2\zeta\omega_n$$

- ***Four equations must be satisfied with five variables (C_B, L_1, L_2, M, ω_n, and $\zeta = 2/\sqrt{2}$). Out of numerous solutions, what is the best transfer function that maximizes the bandwidth, $\omega_{3dB,T-Coil}$?***

Asymmetric T-Coil

- **No closed-form analytical solution was found.**
- **So, first assume L_1=L, L_2=bL, M= mL, with constraint of the coupling coefficient**

$$k = \frac{M}{\sqrt{L_1 L_2}} = \frac{m}{\sqrt{b}} < 1$$

[3] S.C.D.Roy, IETE Journal of Research, 2016

Asymmetric T-Coil

- **b=1 (Symmetric T-Coil)**
- b=1, m=0.333 (k=0.333), $L = 0.375R_D^2C_L$, $C_B = 0.125C_L$, $\omega_n = 2.828/R_DC_L$
- **b<1, what are m(k), L, C_B, ω_n? (using Mathematica)**

b=1.0, m= 0.333 (k=0.333), $L = 0.375R_D^2C_L$, $C_B = 0.1250C_L$, $\omega_n = 2.828/R_DC_L$

b=0.9, m= 0.378 (k=0.398), $L = 0.406R_D^2C_L$, $C_B = 0.1074C_L$, $\omega_n = 2.939/R_DC_L$

b=0.8, m= 0.412 (k=0.460), $L = 0.444R_D^2C_L$, $C_B = 0.0916C_L$, $\omega_n = 3.062/R_DC_L$

b=0.7, m= 0.436 (k=0.521), $L = 0.492R_D^2C_L$, $C_B = 0.0772C_L$, $\omega_n = 3.202/R_DC_L$

b=0.6, m= 0.449 (k=0.580), $L = 0.553R_D^2C_L$, $C_B = 0.0639C_L$, $\omega_n = 3.367/R_DC_L$

b=0.5, m= 0.451 (k=0.638), $L = 0.635R_D^2C_L$, $C_B = 0.0514C_L$, $\omega_n = 3.572/R_DC_L$

b=0.4, m= 0.440 (k=0.696), $L = 0.751R_D^2C_L$, $C_B = 0.0396C_L$, $\omega_n = 3.838/R_DC_L$

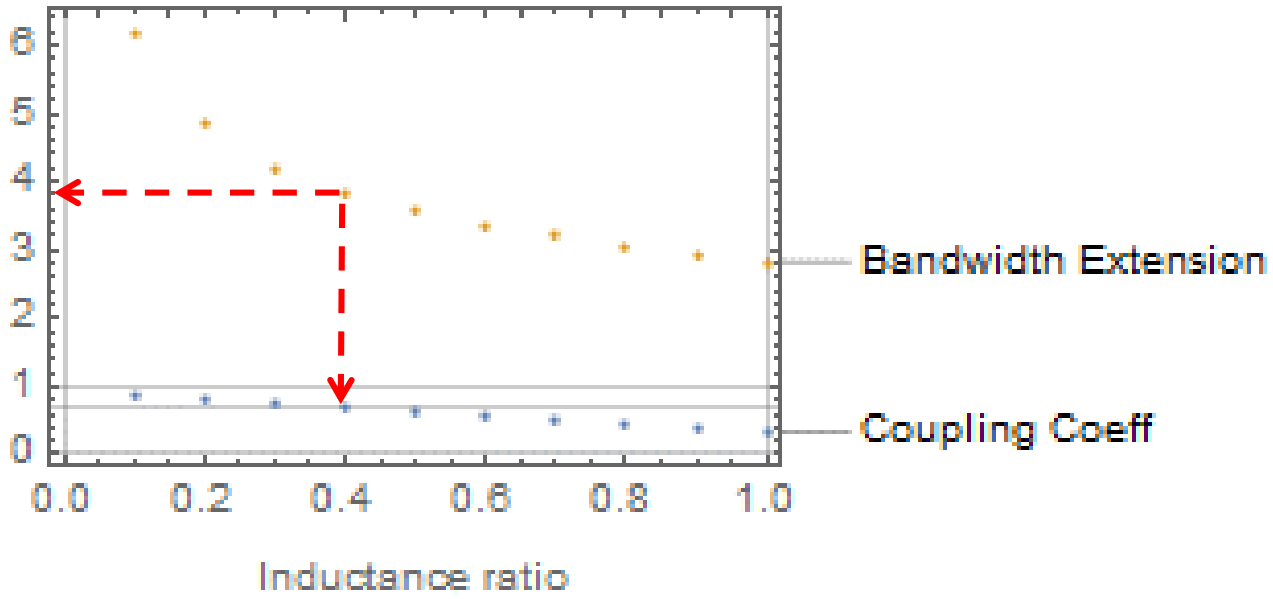
b=0.3, m= 0.414 (k=0.756), $L = 0.931R_D^2C_L$, $C_B = 0.0284C_L$, $\omega_n = 4.215/R_DC_L$

b=0.2, m= 0.366 (k=0.818), $L = 1.250R_D^2C_L$, $C_B = 0.0178C_L$, $\omega_n = 4.828/R_DC_L$

b=0.1, m= 0.280 (k=0.886), $L = 2.028R_D^2C_L$, $C_B = 0.0078C_L$, $\omega_n = 6.176/R_DC_L$

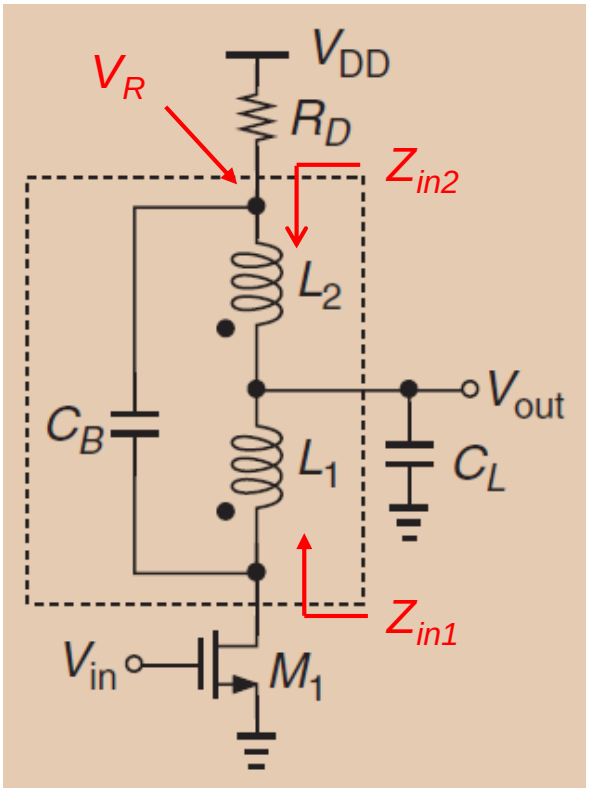
Practical Implementation

- **Coupling coefficient of greater than 0.7 is not practical with on-chip spiral inductor.**
- **So, b=0.4, m= 0.440 (k=0.696), $L = 0.751R_D^2C_L$, $C_B = 0.0396C_L$, ω_n= $3.838/R_DC_L$ is the practical limit.**



[3] S.C.D.Roy, IETE Journal of Research, 2016

Output at Resistor Load



With asymmetric T-coil and $\zeta = 2/\sqrt{2}$,

1) transfer function to R_D?

$$\frac{V_R}{V_{in}}(s) = ?$$

2) impedance seen from either side of the T-Coil?

$Z_{in1} = ?$

$Z_{in2} = ?$

T-Coil Design Flow

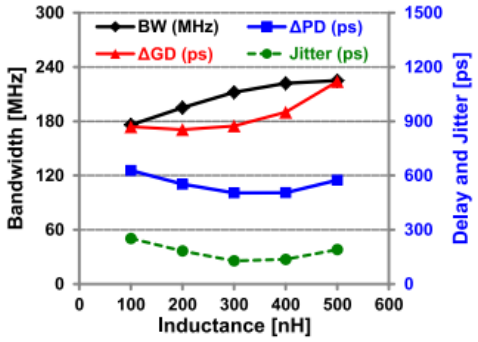
- **Design flow**
  - For given C_L and R_D, determine L_1, L_2, k, and C_B.
  - Design T-coil in a 3-D EM tool and extract S-parameter or circuit model.
  - Perform circuit simulation including parasitic resistance and capacitance.

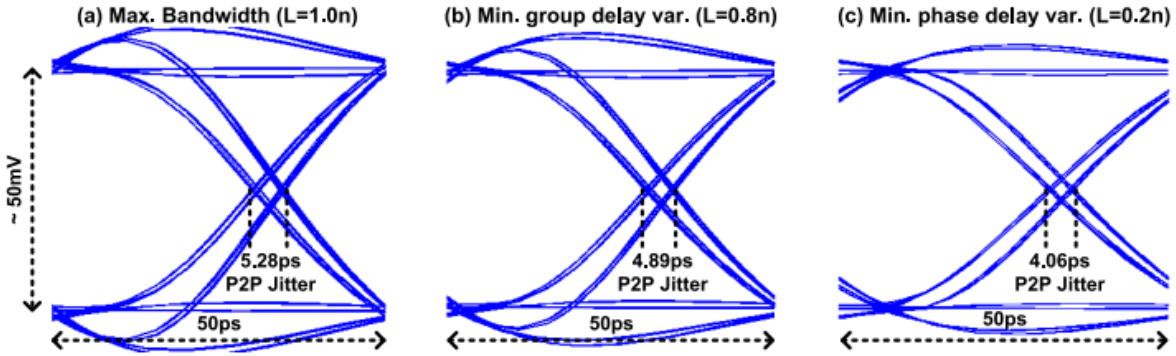
- **Parasitic RC**
  - If using top metal, a 100 pH of inductor has series resistance of **5 ~ 10 Ω**.
  - Natural bridge capacitance is known to be **10 ~ 30 fF**.

- **Realistic limitation**
  - **k can't be over +0.7** in the chip.
  - **Self-resonance** limits large k and L.

Eye Diagram Optimization

- **Maximally Flat Gain ($\zeta = 1/\sqrt{2}$) vs Maximally Flat Phase Delay ($\zeta = 1$)**





- **Minimum Jitter Condition: Minimum phase delay variation**

[4] W Bae, TVLSI, 2017

Asymmetric T-Coil Simulation

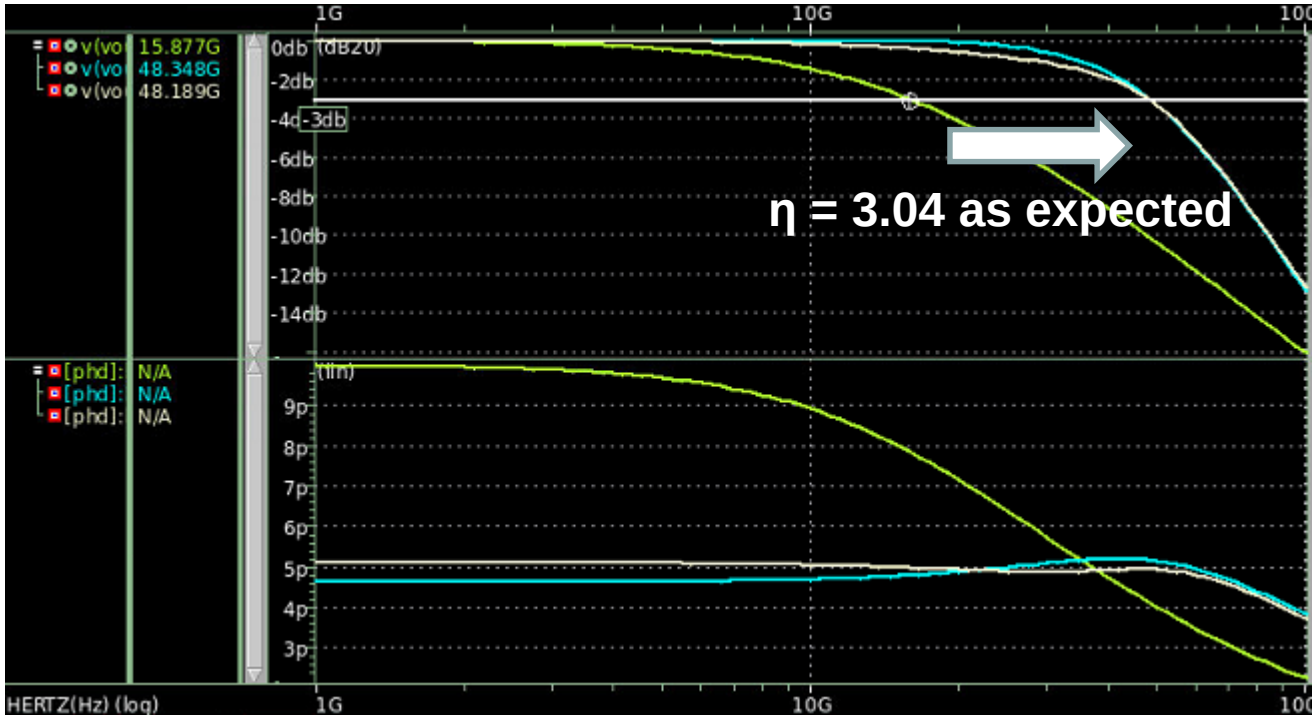
C_L = 200 fF, R_T = 50 Ω
(BW = 15.92 GHz)

ζ = 1/√2, k = 0.45
L = 219 pH, b = 0.815
C_B = 18.74 fF

Two T-coils :
1. Maximally flat gain @ k = 0.45
2. Maximally flat phase delay around 1. (L = 200 pH)

Gain:
No T-coil
T-coil 1
T-coil 2

Phase delay:
No T-coil
T-coil 1
T-coil 2



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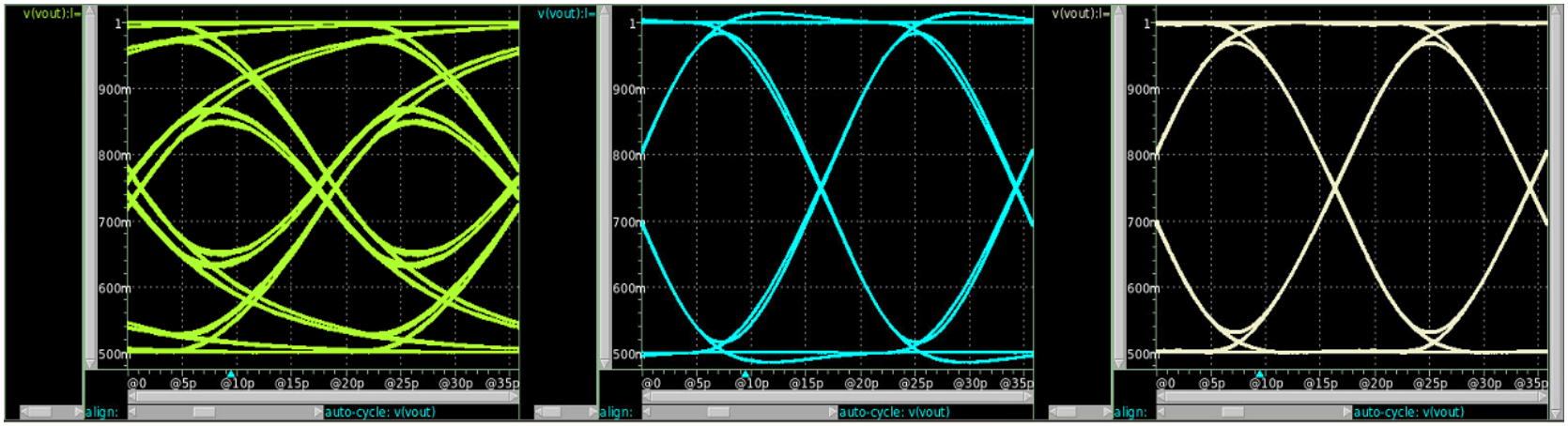
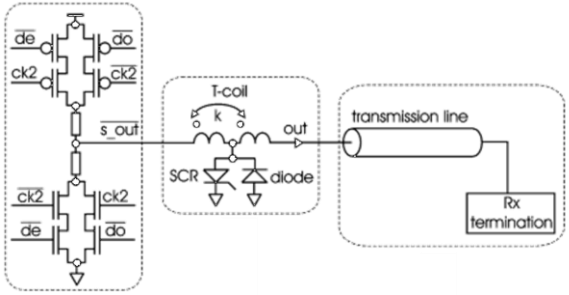
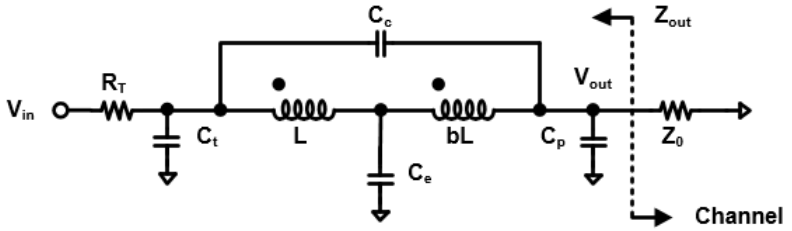
No T-coil | T-coil 1 | T-coil 2

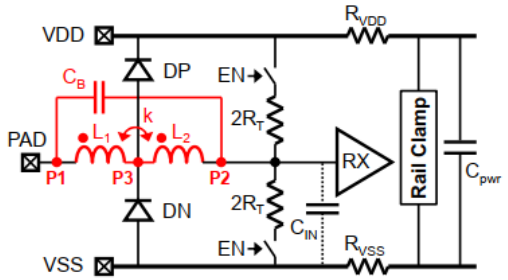


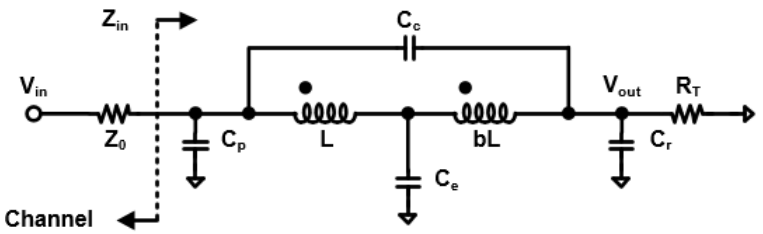
Return Loss Reduction

- **Minimize Return Loss at TX driver and RX receiver.**





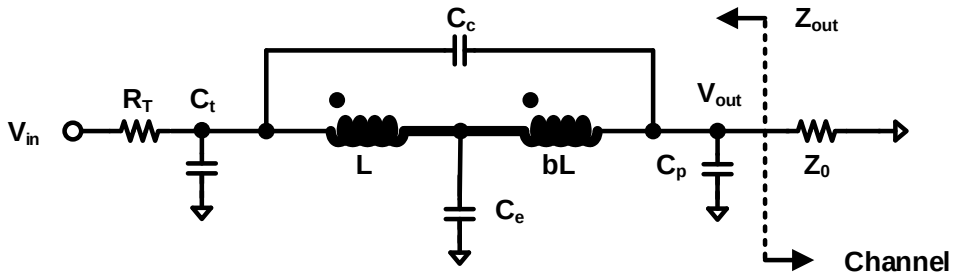




- **Effect of Large ESD Capacitance is removed.**

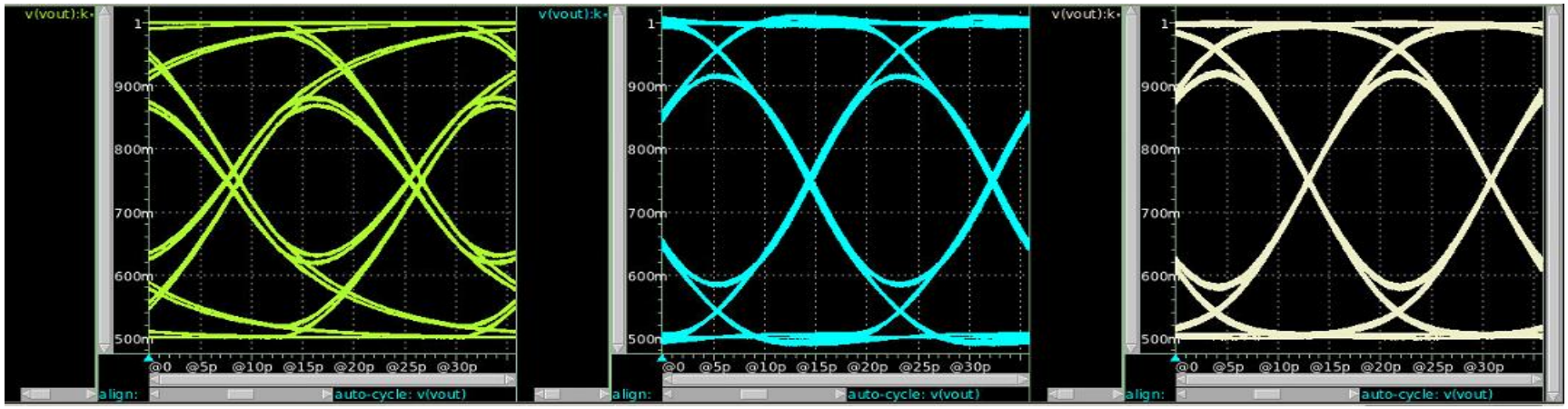
[5] M.Kossel, JSSC, 2008
[6] M.S.Keel, EOS/ESD, 2015

TX Optimization



C_p	200 fF
C_t	50 fF
C_e	100 fF
R_T, Z_0	50 Ω

56Gb/s eye diagram

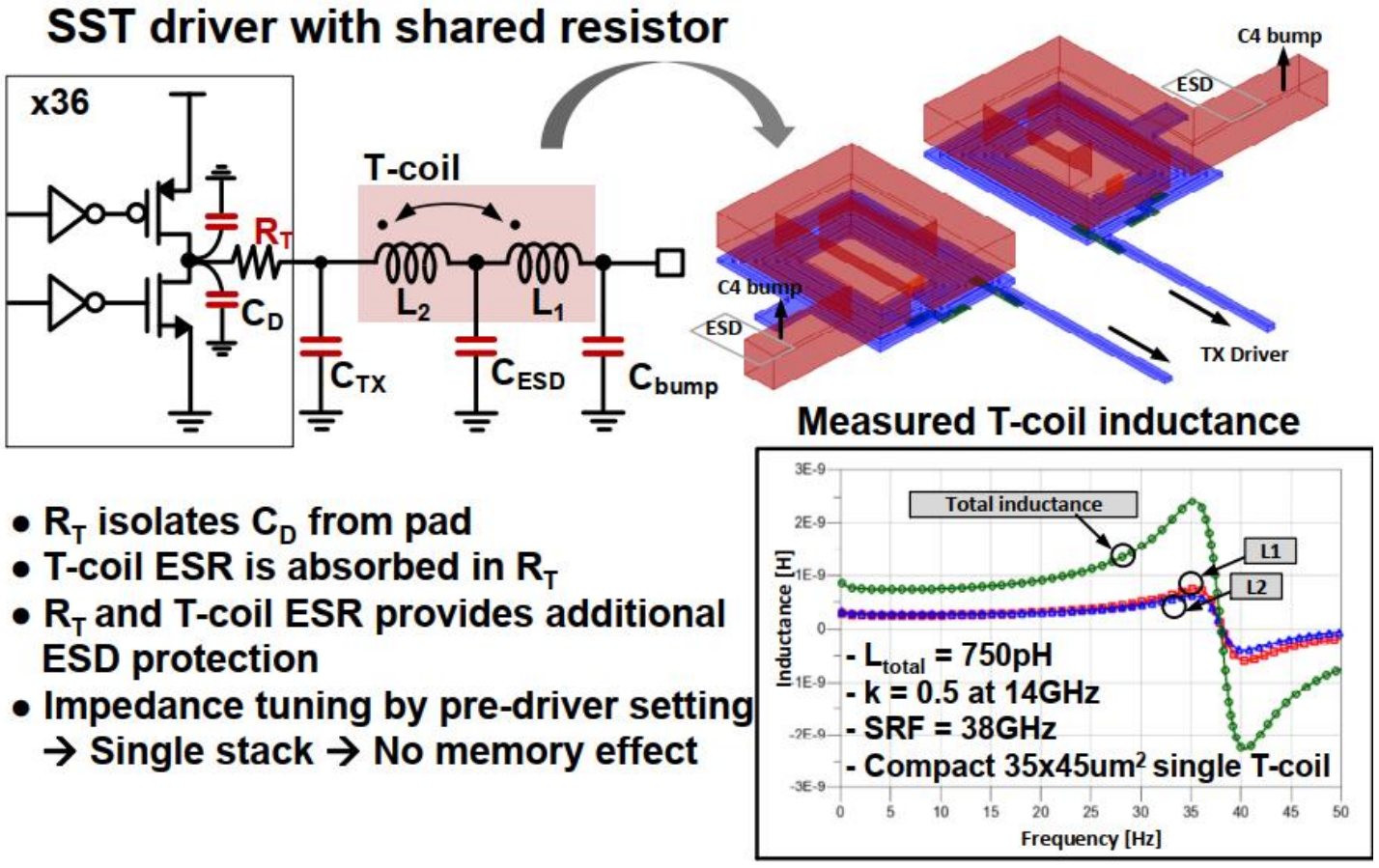


No T-coil

k = 0.5, L = 200 pH, b = 0.3

k = -0.25, L = 250 pH, b = 0.4

Example: ESD Diode Isolation



- R_T isolates C_D from pad
- T-coil ESR is absorbed in R_T
- R_T and T-coil ESR provides additional ESD protection
- Impedance tuning by pre-driver setting → Single stack → No memory effect

3.5: A 16-to-40Gb/s Quarter-Rate NRZ/PAM4 Dual-Mode Transmitter in 14nm CMOS

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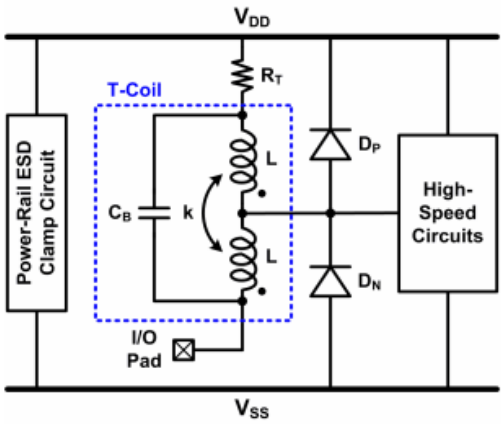
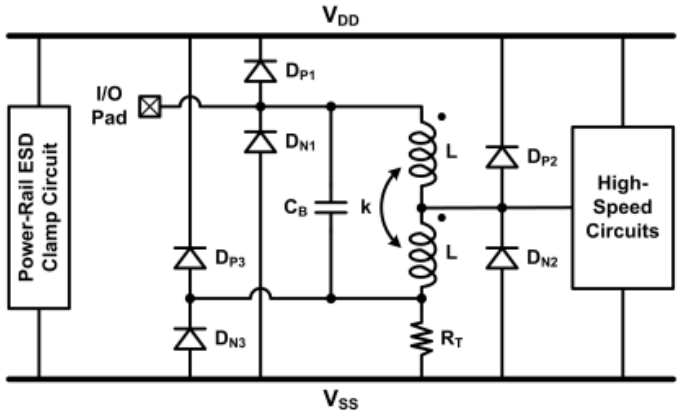
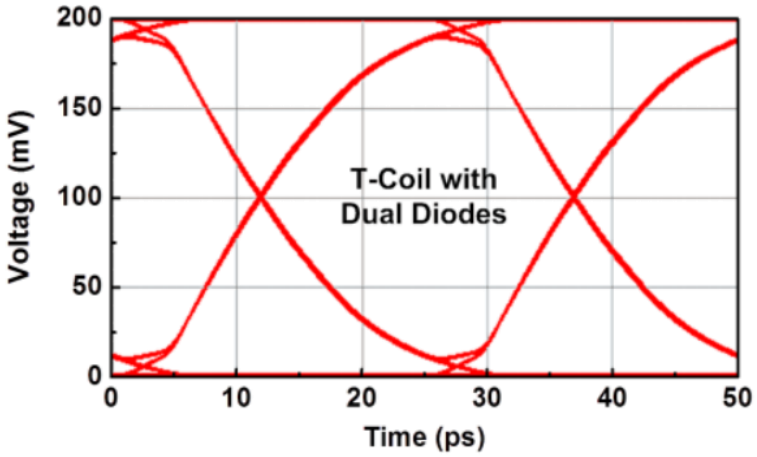
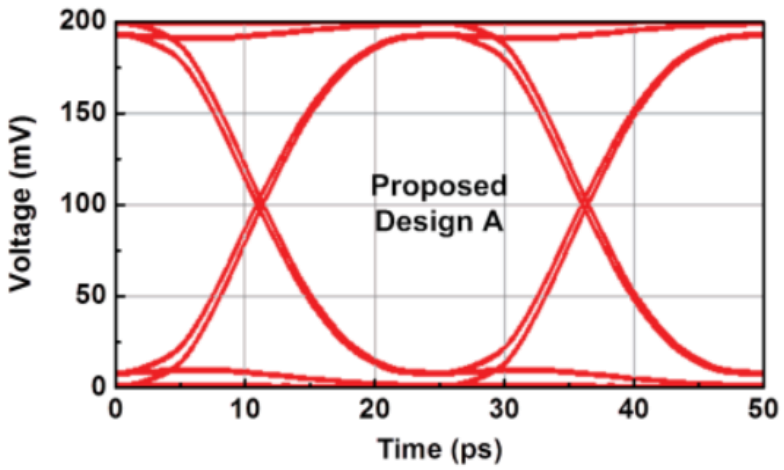
[7] J.Kim, ISSCC, 2015

Example: ESD Separation



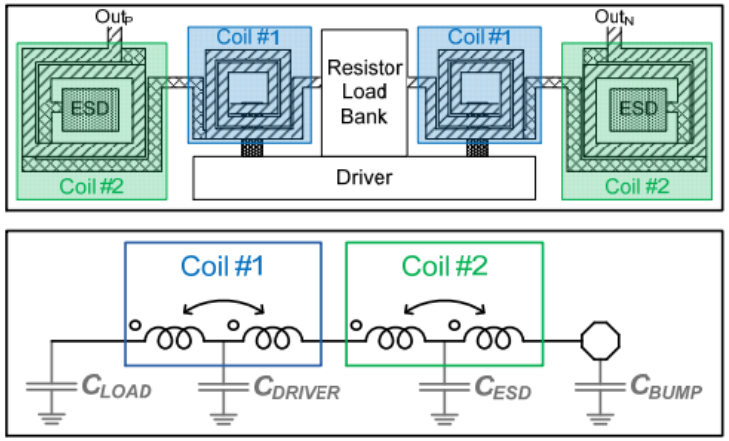


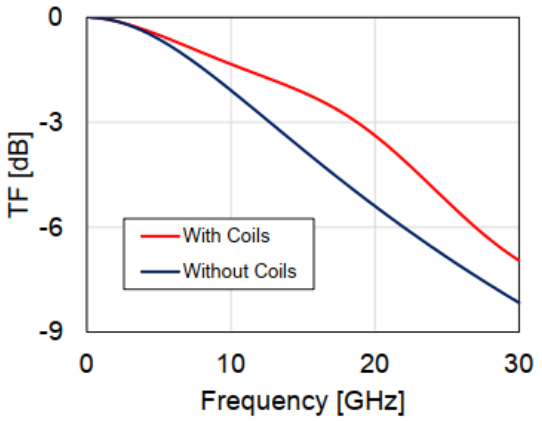




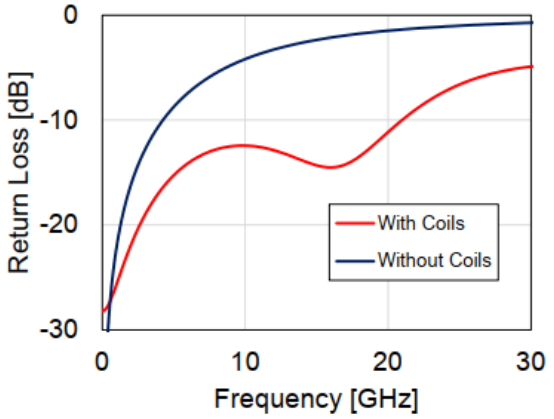
[8] C.Y.Lin, IEEE Transactions on Electron Devices. 2013

Example: Double T-Coil



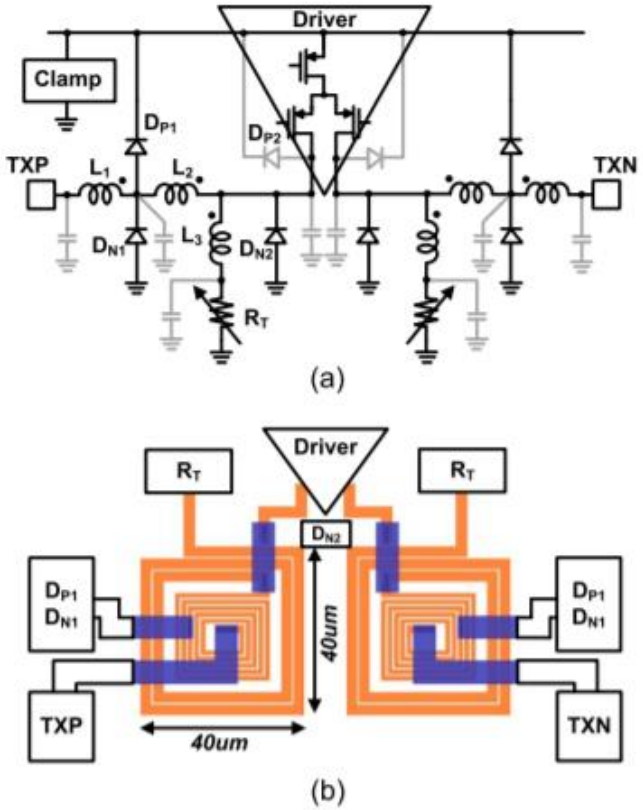


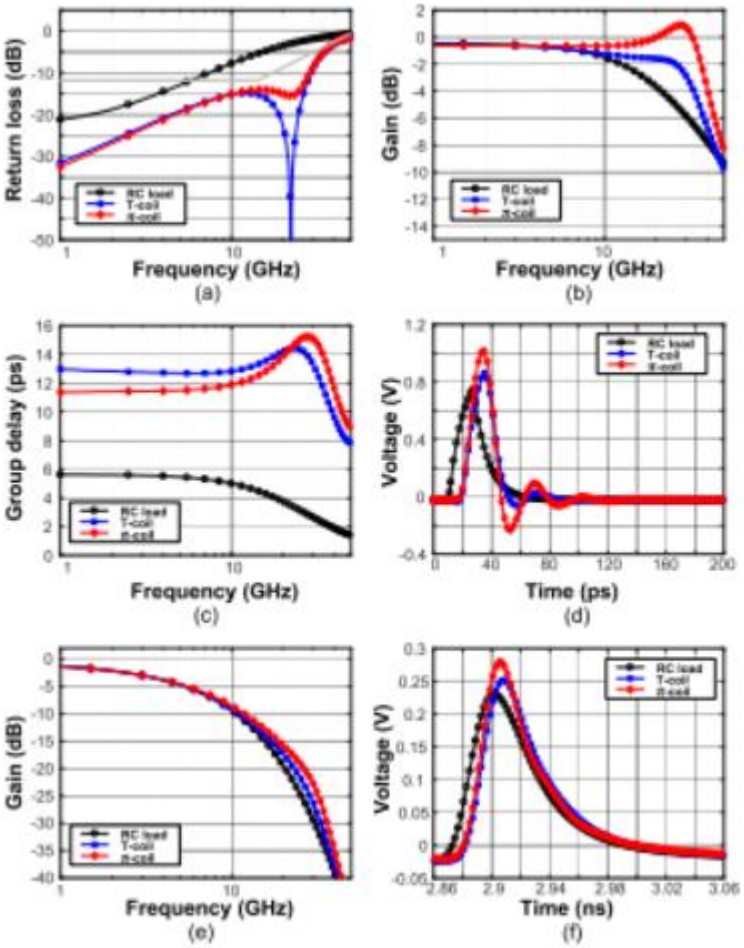
- 200V MM / 500V CDM, >>2kV HBM ESDs
- Driver capacitance is comparable with ESD capacitance
- Double T-coil network enhances bandwidth by 1.5 and improves impedance matching at high frequency



[9] G.Steffan, ISSCC, 2017

Example: π Coil with 4 ports





[10] J Kim, JSSC, 2019

References

[0] E. Ginzton et. al, “Distributed Amplification,” *Proc. IRE*, vol. 36, pp. 956–969, Aug. 1948.

[1] Razavi, Behzad, "The bridged T-coil [a circuit for all seasons]." IEEE Solid-State Circuits Magazine 7.4 (2015): 9-13.

[2] Paramesh, Jeyanandh, and David J. Allstot. "Analysis of the bridged T-coil circuit using the extra-element theorem." IEEE Transactions on Circuits and Systems II: Express Briefs 53.12 (2006): 1408-1412.

[3] Dutta Roy, Suhash C. "A Theoretical Investigation into the Limits of Bandwidth Enhancement with the Asymmetrical Bridged T-Coil Network." IETE Journal of Research 62.3 (2016): 379-386.

[4] Bae, Woorham, Borivoje Nikolić, and Deog-Kyoon Jeong. "Use of phase delay analysis for evaluating wideband circuits: An alternative to group delay analysis." IEEE Transactions on Very Large Scale Integration (VLSI) Systems 25.12 (2017): 3543-3547.

[5] Kossel, Marcel, et al. "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 Journal of Solid-State Circuits 43.12 (2008): 2905-2920.

[6] Keel, Min-Sun, and Elyse Rosenbaum. "CDM-reliable T-coil techniques for high-speed wireline receivers." 2015 37th Electrical Overstress/Electrostatic Discharge Symposium (EOS/ESD). IEEE, 2015.

References

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