

EECS 142



Integrated Circuits for Communication

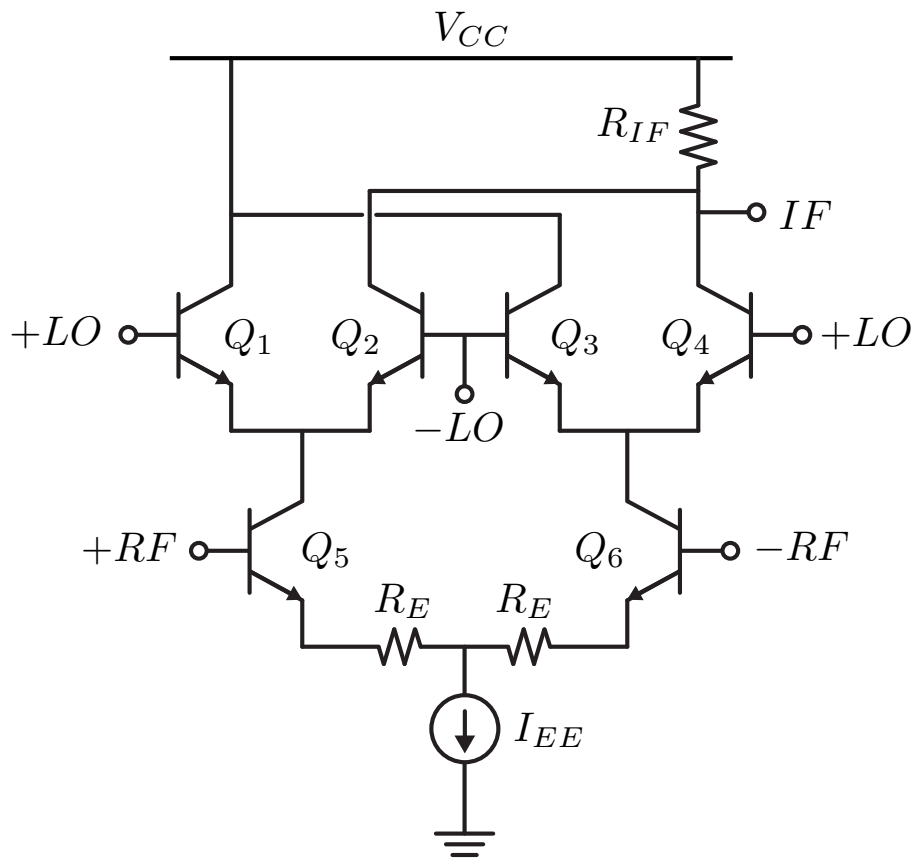
Lecture 18: Balanced Mixers/PNoise and PSS/Transformers

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Double Balanced Mixer

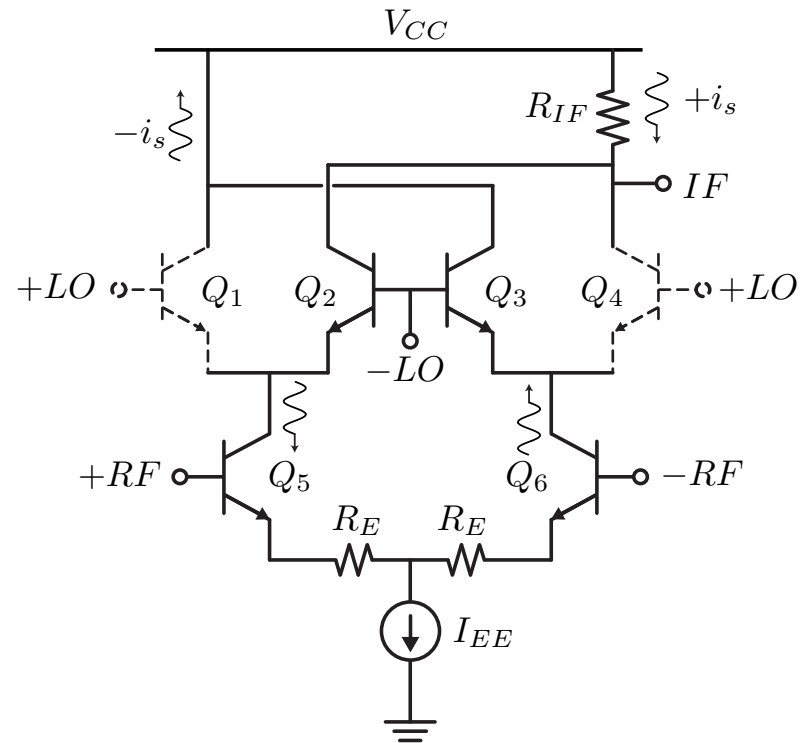
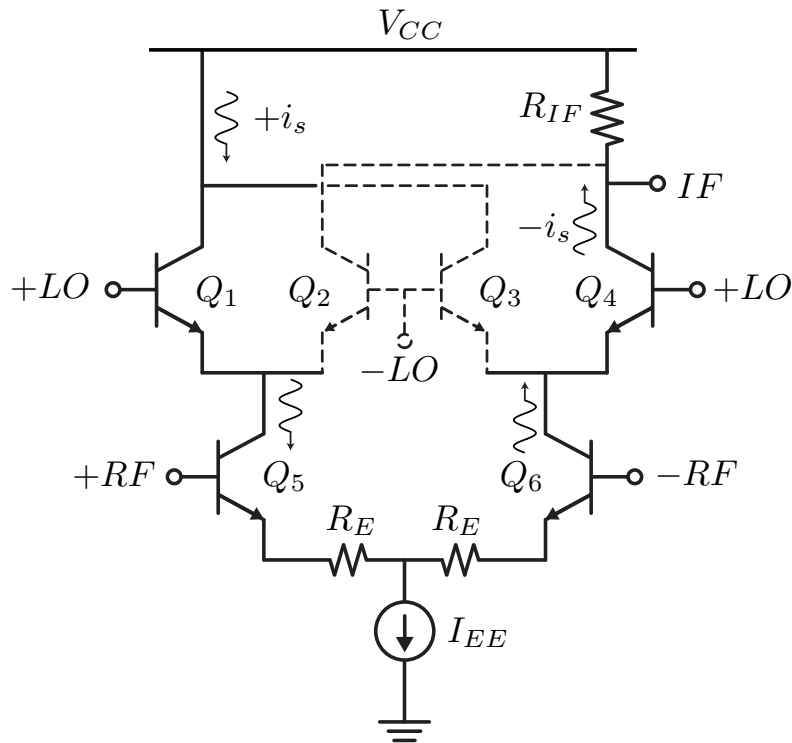


- The single balanced Gilbert cell with differential output rejects the RF at the IF port but the LO feed-through remains.
- A double balanced mixer has a differential RF and a differential LO (double balanced)

Double Balanced Mixer LO Rejection

- As before, the RF stage is a transconductance stage. Degeneration can be used to linearize this stage.
- Because the bias current at the output is constant $I_{EE}/2$ regardless of the LO voltage, the LO signal is rejected. This relies on good matching between transistor Q2 and Q4.
- The differential operation also rejects even order distortion. Viewed as two parallel Gilbert cells, this mixer is also more linear as it processes only half of the signal.
- The noise of this mixer, though, is higher since the noise in each transistor is independent.

Mixer Operation



- The AC operation nearly identical to a single balanced Gilbert cell.
- Even a single ended output, though, effectively multiplies the signal by ± 1 , thus rejecting the RF signal.

Mixer Noise Definition

- By definition we have $F = \frac{SNR_i}{SNR_o}$. If we apply this to a receiving mixer, the input signal is at the “RF” and the output signal is at “IF”. There is some ambiguity to this definition because we have to specify if the RF signal is a single or double sideband modulated waveform.
- For a double sideband modulated waveform, there is signal energy in both sidebands and so for a perfect multiplying mixer, the $F = 1$ since the IF signal is twice as large since energy from both sidebands fall onto the IF. For a single-sideband modulated waveform, though, the noise from the image band adds doubling the IF noise relative to RF. Thus the $F = 2$.
- If an image reject filter is used, the noise in the image band can be suppressed and thus $F = 1$ for a cascade of a sharp image reject filter followed by a multiplier.

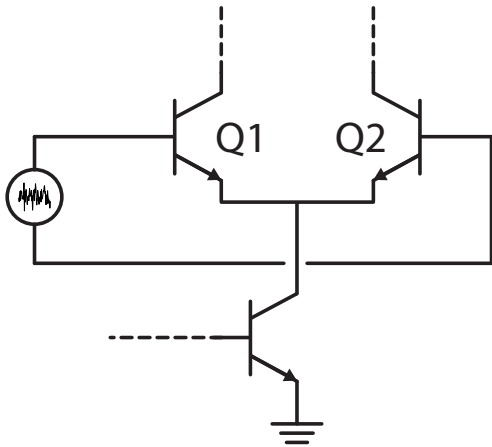
Mixer Noise Folding

- Since the mixer will downconvert any energy at a distance of IF from the LO and its harmonics, all the noise from these image bands will be downconverted to the same IF.
- For a Gilbert cell type mixer, the current of the G_m stage produces white noise which is downconverted. Summing over all the harmonics, we have

$$\sum_{k=-\infty}^{\infty} |c_k|^2 = \frac{1}{T} \int_0^T s(t)^2 dt$$

- where the last equality follows from Parseval's Theorem.
- For a square waveform $s(t)$, the harmonic powers fall like $1/k^2$. Thus the third harmonic contributes about 10% to the switching pair noise.

Mixer Noise Due to Switching Pair



- In addition to the noise folding discussed above, the switching pair itself will contribute noise at IF. If Q1/Q2 are both on, they act as a differential amplifier and introduce noise.
- When only Q1 or Q2 is on, though, the noise is rejected due to the degeneration provided by the transconductance device.
- Thus we generally use a large LO signal to minimize the time when both devices are conducting. It's therefore not surprising that the noise figure of the mixer improves with increasing LO amplitude.

Simulating Mixers with SPICE

- Let's take a typical example of $RF = 1\text{GHz}$, $IF = 1\text{MHz}$. This requires an $LO = RF \pm IF$, close to the RF.
- To resolve the IF frequency components, we need to simulate several cycles of the IF, say 10, so $T_{sim} = 10T_{IF}$
- But that means that we must simulate 10,000 RF cycles

$$\frac{T_{sim}}{T_{RF}} = \frac{10T_{IF}}{T_{RF}} = \frac{10f_{RF}}{f_{IF}} = \frac{10 \cdot 1000}{1} = 10,000$$

- If we are conservative, we may insist that we simulate at least 10 points of the RF cycle, that implies 100,000 points per simulation.
- This is a long and memory intensive simulation. We encountered a similar problem when simulating IM_3

Periodic Steady-State (PSS) Simulation

- Transient simulation is slow and costly because we have to do a tight tolerance simulation of several IF cycles with a weak RF.
- The SpectreRF PSS analysis is a tool for finding the periodic steady-state solution to a circuit. In essence, it tries to find the initial condition or state for the circuit (capacitor voltages, inductor currents) such that the circuit is in periodic steady state.
- It can usually find the periodic solution within 4-5 iterations.
- In the mixer, if we ignore the RF signal, then the periodic operating point is determined by the LO signal alone.

PSS Iteration

- Since typical PSS run converges in 4-5 cycles of the LO, or a simulation time of about $5T_{LO}$, the overall simulation converges several orders of magnitude faster than transient at the IF frequency.
- PSS requires that the circuit is not chaotic (periodic input leads to a periodic output).
- High Q circuits do not pose a problem to PSS simulation since we are finding the steady-state solution. The high Q natural response takes roughly Q cycles to die down, thus saving much simulation time.

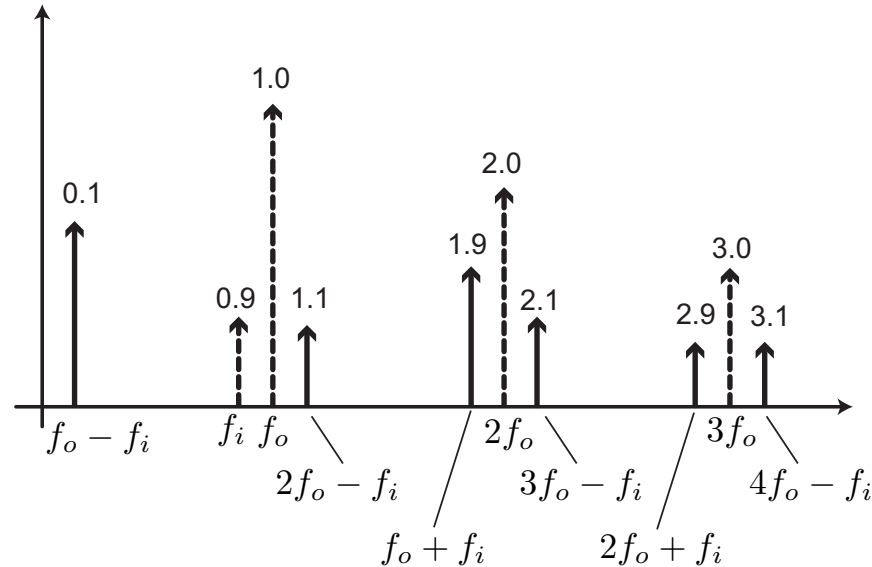
PSS Options

- We can perform PSS analysis on *driven* or *autonomous* circuits. An autonomous circuit has no periodic inputs but produces a periodic output (e.g. an oscillator).
- For PSS analysis we need to specify a list of “large” signals in the circuit. In a mixer, the only large tone is the LO, so there is only one signal to list.
- We also specify the “beat frequency” or the frequency of the resulting periodic operating point. For instance if we drive a circuit with two large tones at f_1 and f_2 , the beat frequency is $|f_1 - f_2|$. Spectre can auto-calculate this frequency.
- An additional time for stabilization t_{stab} can be specified to help with the convergence. For a mixer this is not needed.

Periodic AC (PAC)

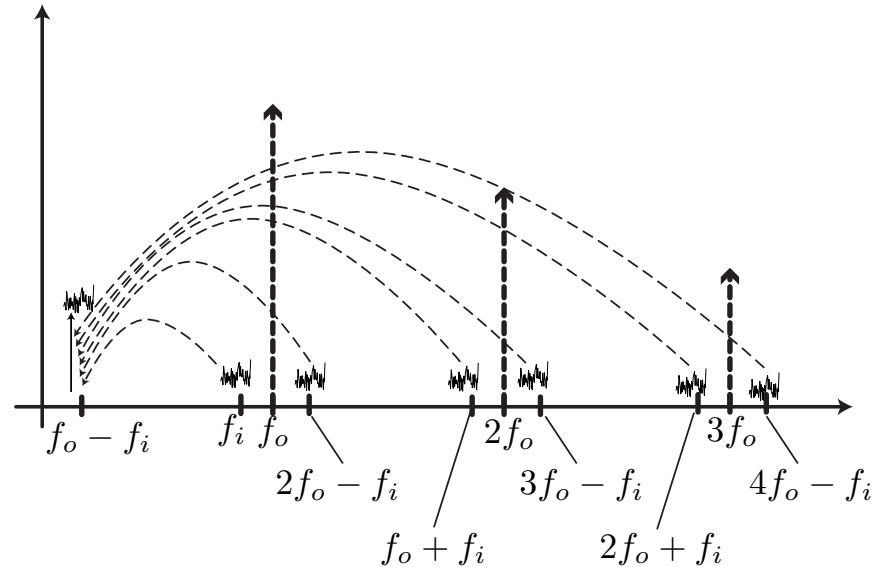
- Once a PSS analysis is performed at the “beat frequency”, the circuit can be linearized about this time varying operating point.
- Note that for a given AC input, there are as many transfer functions as there are harmonics in the LO.
- We specify the frequency range of the AC input signal as either an absolute or relative range. A relative range is a frequency offset with respect to the beat frequency.
- We also specify the maximum sidebands to keep for the simulation. Note that this does not affect the accuracy of the simulation but simply the amount of saved data.

PAC Picture



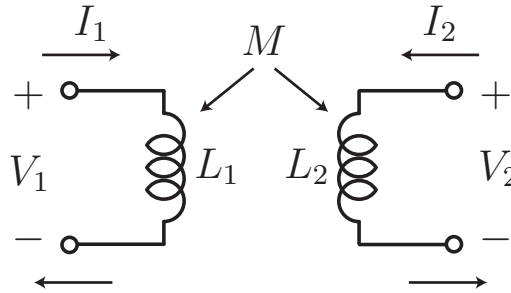
- The input frequency f_i is translated to frequencies $f_i + kf_o$, where f_o is the beat (LO) frequency. The $k = 0$ sideband corresponds to the DC component of the LO signal (e.g. time invariant behavior). The non-zero components, though, correspond to mixing. E.g. $k = -1$ correspond to frequency down-conversion. $k = +1$ is the normal up-conversion. $k = -2$ is the 2nd harmonic mixing $f_i - 2f_o$.

PNoise



- PNoise is a noise analysis that takes the frequency translation effects into account. The simulation parameters are similar to PAC with the exception that we must identify the input and output ports (for noise figure) and the reference side-band, or the desired output frequency. For a mixer, this is $k = -1$.

Coupled Inductors



- Consider a set of coupled inductors. In particular, for two coupled inductors, we have

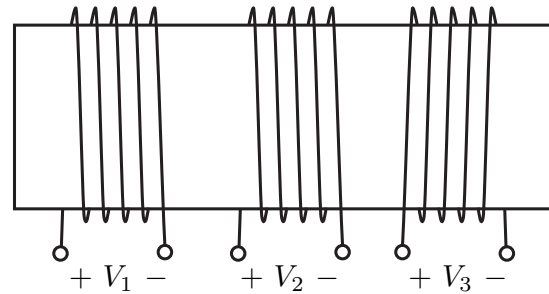
$$V_1 = j\omega L_1 I_1 + j\omega M I_2$$

$$V_2 = j\omega M I_1 + j\omega L_2 I_2$$

- We usually express M as a fraction of the geometric mean:

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

Magnetic Flux



- By imposing physical arguments, we can show that $-1 \leq k \leq 1$. When $M > 0$, a positive current in one winding induces a positive voltage across the second winding. Likewise, $M < 0$ induces a negative voltage.
- Recall that the magnetic flux can couple in a positive or negative orientation depending on the physical orientation of the windings.

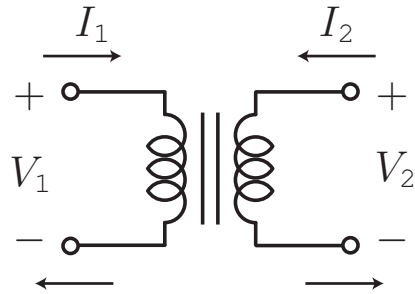
Magnetic Flux (cont)

- Magnetic coupling is due to magnetic flux linkage. A current leads to flux which couples to other nearby circuits. A time-varying flux induces a voltage

$$i \rightarrow \Psi \qquad \frac{di}{dt} \rightarrow \frac{d\Psi}{dt} \rightarrow v$$

- If $|k| = 1$, we say that the inductors (windings) are perfectly coupled. In practice $|k| < 1$ but using a magnetic core, we can come close to ideal.

Ideal Transformer

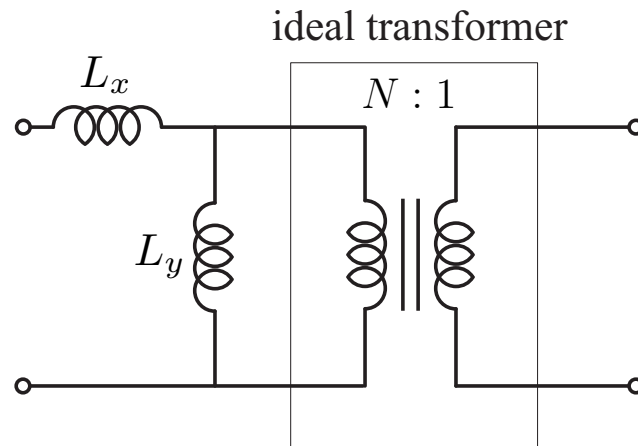


$$V_1 = \frac{1}{N} V_2$$

$$I_1 = N I_2$$

- The ideal transformer has the above current/voltage relationship
- In fact, the second equation is superfluous if we demand energy conservation (e.g. the transformer is a passive device). It is understood that an ideal transformer does not work at DC but at any AC frequency, the above relations hold.
- How do we build such a transformer from coupled inductors?

Coupled Inductor Equivalent Circuit



- We can show that the above circuit is totally equivalent to two coupled inductors. In particular, note that an ideal transformer is embedded into the model. To see this, note that

$$V_1 = j\omega L_x I_1 + \left(I_1 + \frac{I_2}{N}\right) j\omega L_y = j\omega (L_x + L_y) I_1 + \frac{j\omega L_y}{N} I_2$$

$$V_2 = \frac{V_y}{N} = \left(I_1 + \frac{I_2}{N}\right) \frac{j\omega L_y}{N} = I_1 \frac{j\omega L_y}{N} + \frac{j\omega L_y}{N^2} I_2$$

Eq. Circuit Parameters

- We can solve the following three equations to find the equivalence

$$L_1 = L_x + L_y \quad L_2 = \frac{L_y}{N^2} \quad M = \frac{L_y}{N}$$

- Solving for the parameters, we have

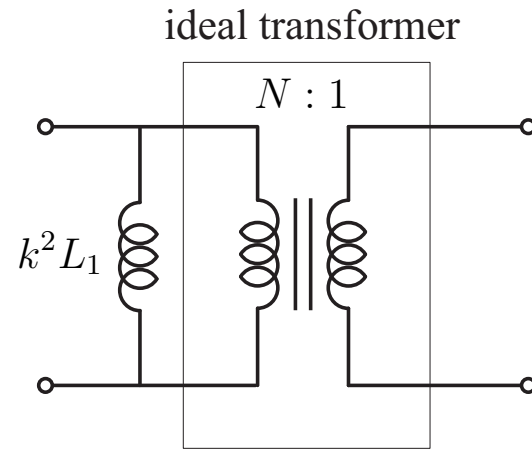
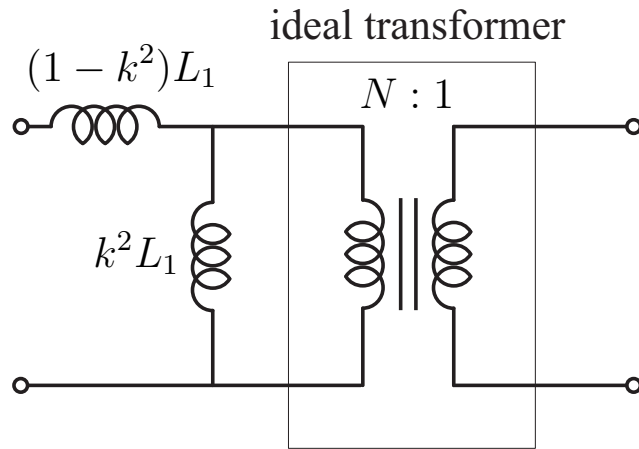
$$L_y = nM = N^2 L_2$$

$$n = \frac{M}{L_2} = \frac{k\sqrt{L_1 L_2}}{L_2} = k\sqrt{\frac{L_1}{L_2}}$$

$$L_y = N^2 L_2 = k^2 \frac{L_1}{L_2} L_2 = k^2 L_1$$

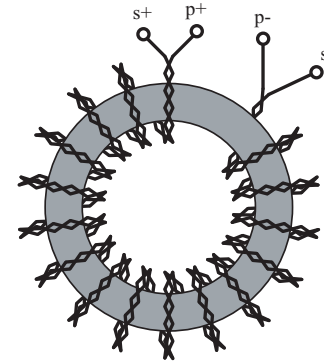
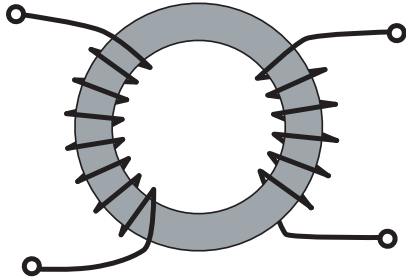
$$L_x = L_1 - L_y = (1 - k^2) L_1$$

Leakage/Magnetization Inductance



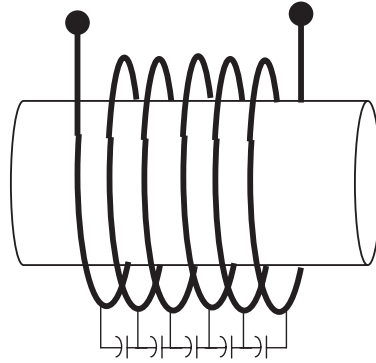
- We identify the parasitic inductors as the “leakage inductance” (because it goes away as $k \rightarrow 1$) and the magnetization inductance.
- We see that even if $k = 1$, two coupled inductors do not behave like an ideal transformer unless $L_1 \rightarrow \infty$
- A large shunt inductor correctly predicts the DC/AC transition (DC currents are shorted)

Transformer Construction



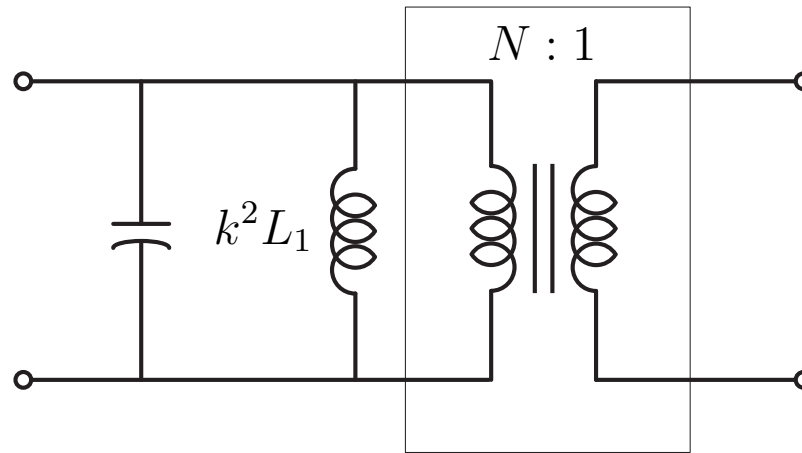
- The transformer on the left is a typical low frequency transformer which uses a core to couple the flux. By isolating the primary and the secondary, there is negligible capacitive coupling.
- The second transformer is a high frequency version, where the wires are twisted together to maximize coupling. The core is inactive at high frequency but the boosted inductance is useful for rejecting common mode currents in the circuit.

High Frequency Transformers



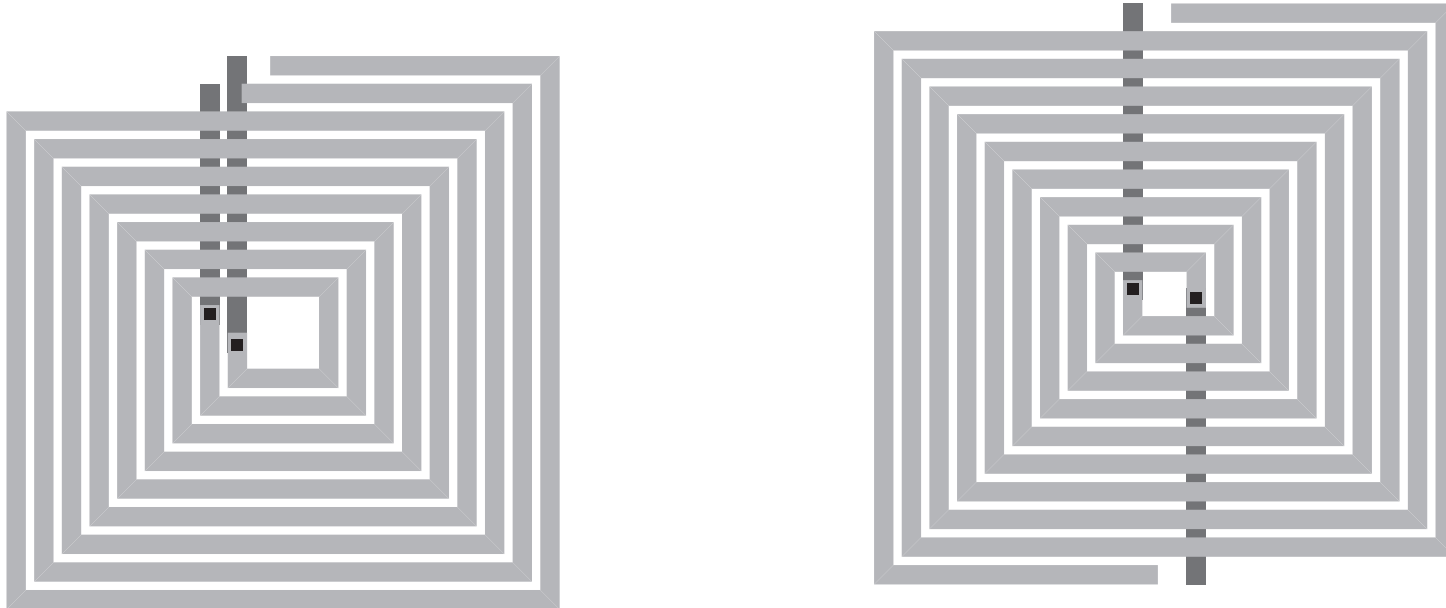
- In high frequency applications, we cannot make L_1 large. In fact, above around 100MHz, magnetic cores are lossy. Without a core, high inductance requires many windings, which ultimately results in excessive winding capacitance and non-magnetic behavior.
- Thus in a high frequency applications $|k| < 1$ and L is finite. If possible, we can ensure that $\omega L \gg Z_0$, where Z_0 is the typical impedances presented to the transformer.

Tuned Transformers



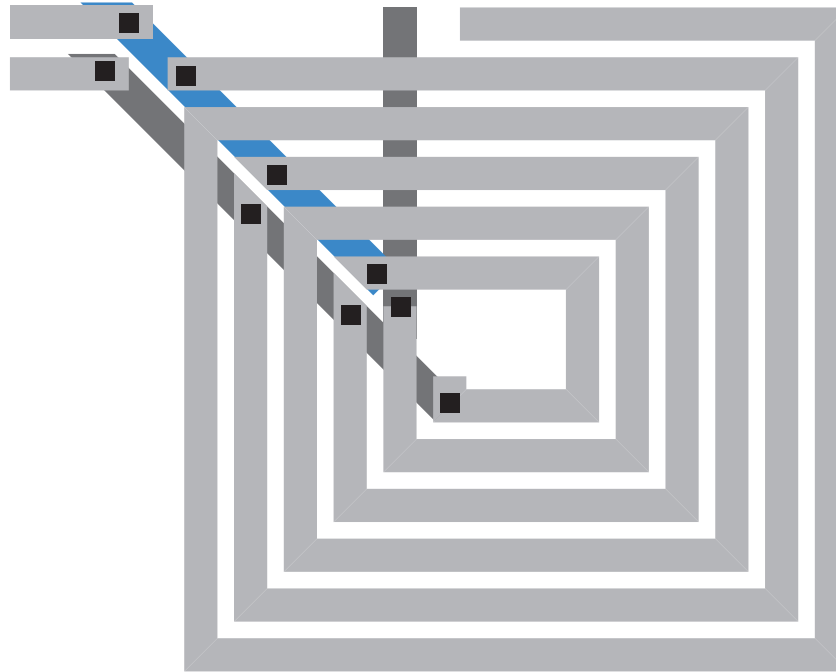
- Otherwise, we can use capacitors to tune away the effects of finite L , resulting in more narrowband matches.

On Chip Transformer Layout



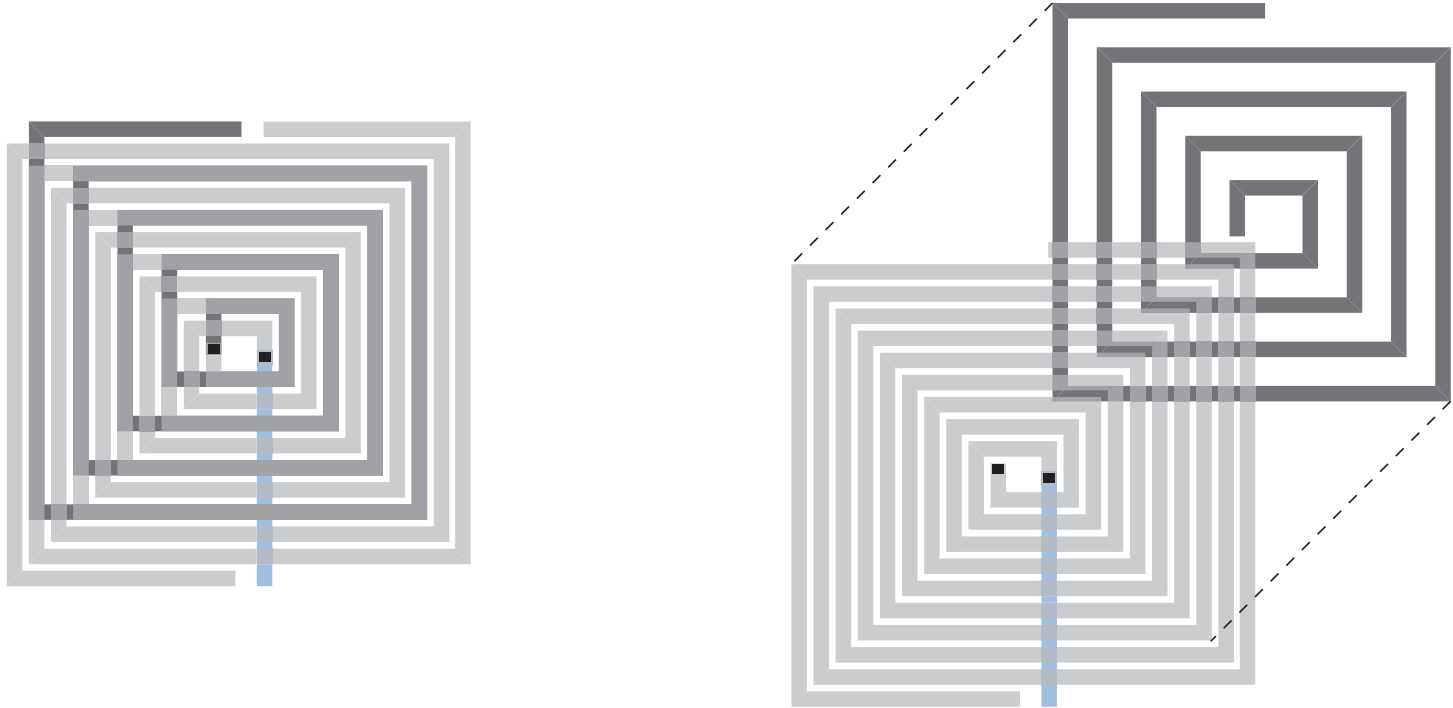
- On-chip structures are planar. Two square spirals wound together form a 1:1 transformer. The “bifilar” layout and “symmetric” bifilar have coupling factors of $0.7 - 0.8$.

N:1 Transformers



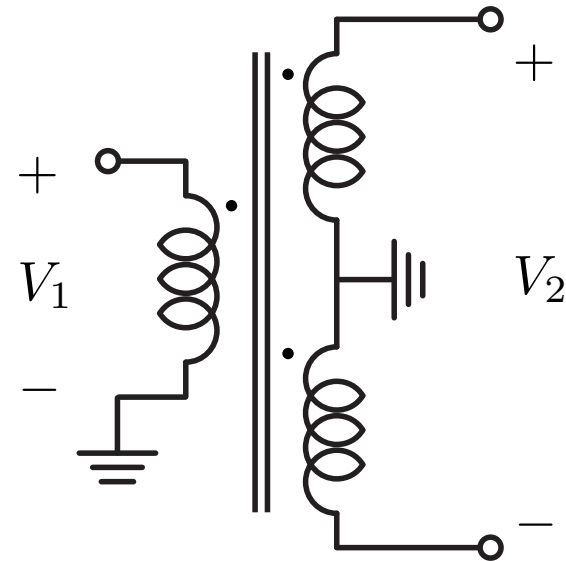
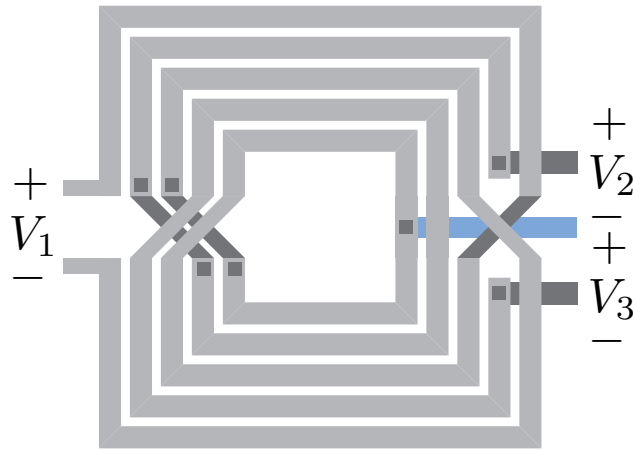
- An $n : 1$ transformer is designed by using fewer turns.
- Alternatively, turns from the secondary can be put in parallel to lower the resistance.

Multi-Layer Transformers



- Multiple metal layers can be utilized to form more compact and higher coupling factor structures.
- The primary is connected on the top two metal layers (in series), forming a high inductance. The secondary is a single layer inductor.

Baluns



- A balun is useful for converting single-ended single into balanced (differential) signals. The inverse is also easily accomplished.
- A symmetric single layer transformer balun layout is shown above. The common center can be connected to AC ground.