Application Notes

Coupling Effects Between Lumped Elements

Inder J. Bahl

Low-cost radio-frequency (RF) and microwave components mandate a higher level of integration and more circuit functions in a smaller package. Lumped elements are commonly used due to their smaller size, lower parasitic effects, larger bandwidths, and large impedance transformation ratio capability. When such components are placed in close proximity to each other, a fraction of the power present on the main component is coupled to the secondary element. The power coupled is a function of the physical dimensions of the structure, mode of propagation, transverse electromagnetic (TEM) or non-TEM, the frequency of operation, and the direction of propagation of the primary power. In these structures, there is a continuous coupling between the electromagnetic fields of the two components known as parasitic coupling.

In compact circuits, inductors, capacitors, and vias are placed in close proximity to each other; fields from one inductor terminate on another inductor, capacitor, or via pad resulting in modified characteristics, depending upon the separation between the components. The modified characteristics affect the electrical performance of the circuit in several ways. It may change the frequency response in terms of frequency range and bandwidth and degrade the gain/insertion loss and its flatness; input and output voltage standing wave ratio (VSWR); and many other characteristics, including output power, power-added efficiency, and noise figure, depending on the type of circuit. This coupling can also result in the instability of an amplifier circuit, create a feedback resulting in a peak or a dip in the measured gain response, or make a substantial change in a phase-shifter response. In general, this parasitic coupling is undesirable and an impediment in obtaining an optimal solution in a circuit design; however, this

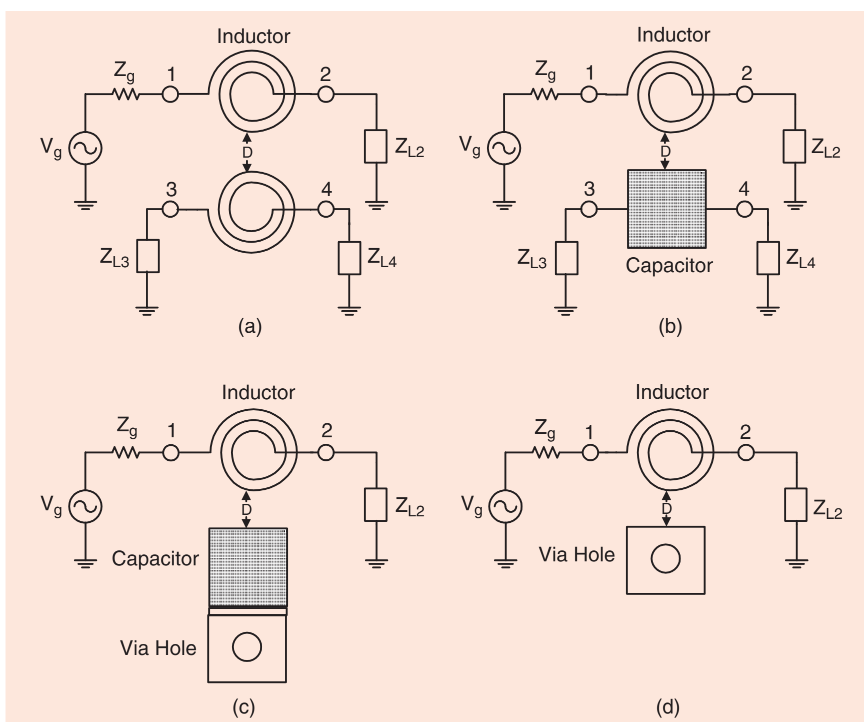

Figure 1. *Different configurations of coupled lumped elements.*

I.J. Bahl is with M/A-COM, Inc. Roanoke, Virginia, USA.

effect can be reduced by placing metal-filled via holes, known as via fence [1]-[4], or by using proper orientation of inductors [5] in the layout of the circuit. At the circuit level, the via fence approach is not practical as it occupies appreciable area. Alternatively, the coupling effect can be taken into account in the design by performing electromagnetic (EM) simulations, or, at a given frequency, it can be reduced to an acceptable level by maintaining a large enough distance on the order of substrate thickness between the circuit elements [6].

For example, the coupling between two closely placed inductors depends upon several factors, including shape of the inductors, separation between the inductors, size of each inductor and their orientation, resistivity of the substrate on which they are printed, and the frequency of operation. The coupling effects between circuit elements shown in Figure 1 are discussed in terms of coupling coefficients, and change in input impedance and transmission phase of the inductor. The generator, or source impedance, Z_g is 50 Ω, and $Z_{Li}(i = 2,3,4)$ are the terminating impedances at various ports. The minimum separation between two elements is denoted by D. Coupling between inductors is described, including circular and rectangular shapes and three orientations as shown in Figure 2. All structures discussed in this paper are designed on a 75 μm thick GaAs substrate.

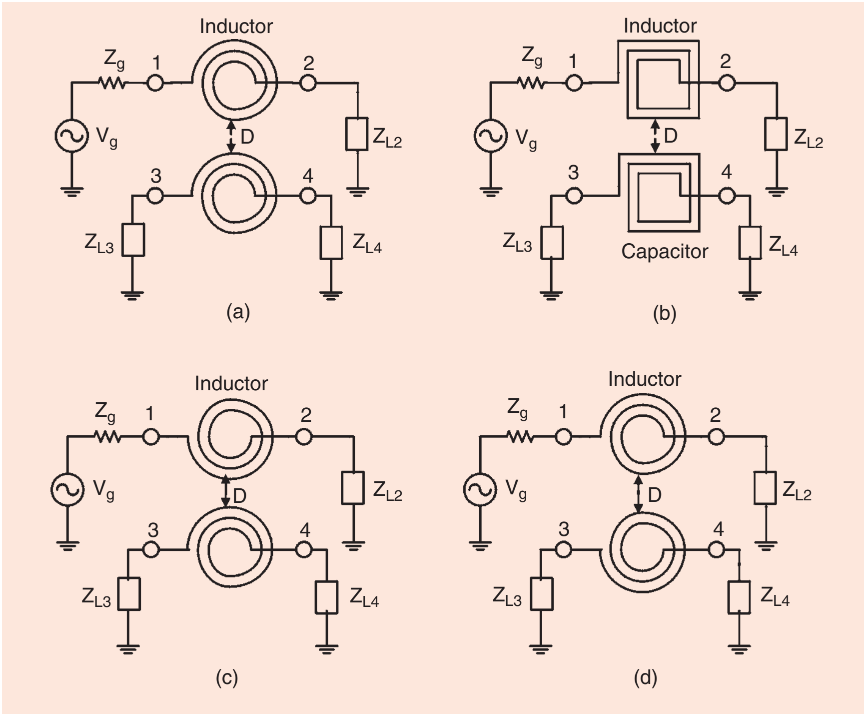

Figure 2. *Several configurations of inductors placed in close proximity.*

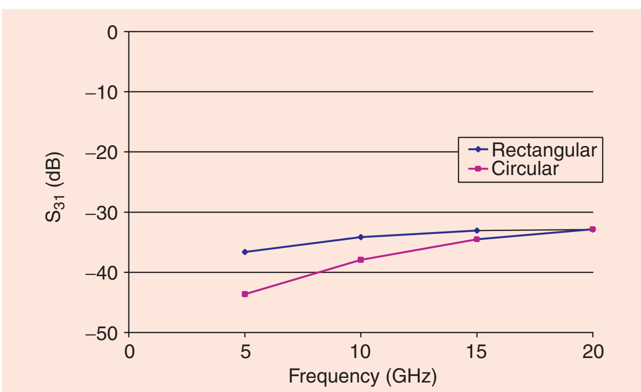

Figure 3. *Comparison of coupling coefficient versus frequency for circular and rectangular 0.8 nH spiral inductors having similar areas. D = 20 μm.*

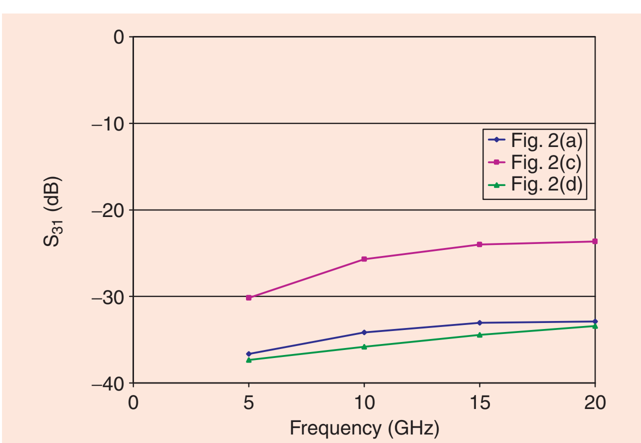

Figure 4. *Coupling between circular inductors for three different orientations shown in Figure 2. D = 20 μm.*

Coupling Between Inductors

For a given inductance value and a distance between two spiral inductors, the coupling between the circular spirals shown in Figure 2(a) is lower than the rectangular spirals shown in Figure 2(b), because of the larger average coupled distance. Figure 3 shows the coupling coefficient between ports 3 and 1 as a function of frequency for 0.8 nH circular and rectangular inductors placed 20 μm apart. Dimensions for the circular inductors are: line width $W = 12$ μm, line spacing $S = 8$ μm, inner diameter $D_i = 50$ μm, and number of turns $n = 2.5$. The rectangular inductors have same dimensions, except it has 11 sections. Here all ports are terminated in 50 Ω. The coupling between ports 3 and 1 is slightly higher than between ports 4 and 1.

The coupling effects between two circular spiral inductors in three different possible orientations, shown in Figure 2, were also investigated. Each inductor has 12 μm conductor width, 8 μm spacing, 4.5 μm thick conductors, and 50 μm inner diameter. The separation between the inductors varied from 20 to 200 μm. Figure 4 shows the simulated coupling between ports 3 and 1, when other two ports were terminated in 50 Ω, for 20 μm spacing as a function of frequency. Among all

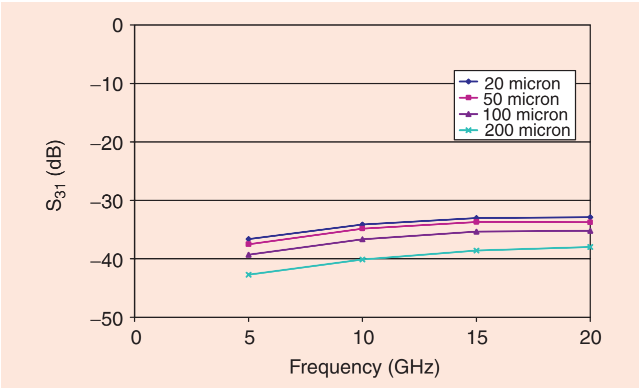

Figure 5. *Coupling between inductors shown in Figure 2(a) for various separations.*

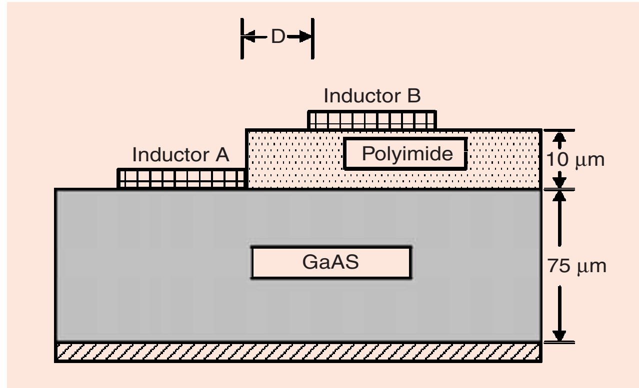

Figure 6. *Cross-section view of the multilayer inductors.*

three configurations, coupling between ports 3 and 1 is slightly higher than between ports 4 and 1. The configurations shown in Figure 2(c) and (d) result in highest and smallest coupling, respectively. The difference between these two configurations is about 10 dB. Thus, the orientation of the inductor coil significantly affects the parasitic coupling between the two. Similar results have been reported for the rectangular spiral inductors [5]. Therefore, in the layout of such inductors, extra care must be exercised to minimize the parasitic coupling. Figure 5 shows the coupling at 10 GHz as a function of separation between the inductors. As distance increases, the coupling decreases monotonically.

We also performed the analysis of coupling between the multilayer circular inductors. As shown in Figure 6, inductor

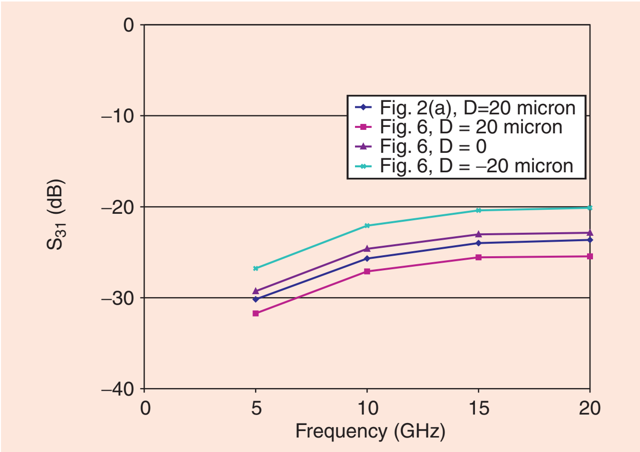

Figure 7. *Comparison of coupling between inductors shown in Figure 6 and in Figure 2(a).*

Table 1. Percentage change in the input impedance (Z_{in}) of an inductor due to another inductor's close proximity. $D = 20$ µm.

Inductor Configuration	Re [ΔZ_{in}] Ω (%)		Im [ΔZ_{in}] Ω %	
	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz
Figure 2(a)	0.9	2.7	–0.02	0.6
Figure 2(c)	14.6	17.6	–0.06	–0.65

A is placed directly on GaAs substrate, whereas inductor B is placed on 10 µm thick polyimide backed by GaAs substrate. The distance D is from edge to edge, and a negative value designates the overlap distance. The inductor dimensions are the same as discussed previously. The orientation of Figure 6 inductors is the same as shown in Figure 2(a).

Figure 7 shows the coupling between ports 3 and 1, and Table 1 summarizes the effect of inductor B on the input impedance of inductor A.

Coupling Between Inductor and MIM Capacitor

The coupling between a 0.8 nH inductor and a 10 pF metal-insulator-metal (MIM) capacitor (180 × 180 µm) is shown in Figure 1(b). The simulated data is summarized for various port termination conditions in Tables 2 and 3. In this case, the change in input impedance of the inductor when port 2 is short circuited and the change in the transmission phase when port 2 is terminated in 50 Ω are also evaluated with respect to an isolated inductor. The capacitor ports 3 and 4 are terminated in 50 Ω. The results are summarized in Table 4 as a function of separation distance D. For such a structure, the effect is less than 1% at 10 GHz and lower frequencies when the distance is 20 µm. Table 5 summarizes results for a case when the 10 pF capacitor is grounded as shown in Figure 1(c). The proximity effects are similar to those in Table 4.

Table 2. Magnitude of S_{31} (dB) between inductor and capacitor under various termination conditions of ports 2 and 4. Z_{L3} = 50 Ω.

Z_{L2}	Z_{L4}	6 GHz	10 GHz	20 GHz
∝	∝	–37	–35	–47
50 Ω	50 Ω	–39	–35	–30
0	0	–37	–35	–37
0.5 pF	0.5 pF	–37	–35	–47
50 Ω	∝	–41	–38	–38
50 Ω	0	–41	–38	–37
50 Ω	0.5 pF	–41	–38	–38

Table 3. Magnitude of S_{41} (dB) between inductor and capacitor under various termination conditions of ports 2 and 3. Z_{L4} = 50 Ω.

Z_{L2}	Z_{L3}	6 GHz	10 GHz	20 GHz
∝	∝	–37	–34	–29
50 Ω	50 Ω	–52	–45	–35
0	0	–37	–34	–29
0.5 pF	0.5 pF	–37	–34	–29
50 Ω	∝	–41	–37	–45
50 Ω	0	–41	–37	–33
50 Ω	0.5 pF	–41	–37	–31

Coupling Between Inductor and Via Hole

The proximity effects of a via hole (180 × 180 µm) on the characteristics of a 0.8 nH inductor have been investigated; Figure 1(d)

Table 4. Percentage change in the input impedance (Z_{in}) and transmission phase of an inductor due to 10 pF capacitor's close proximity.

Distance D (µm)	Re [ΔZ_{in}] Ω (%)		Im [ΔZ_{in}] Ω %		Δ[Ang.S_{21}]° (%)	
	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz
20	0.71	4.10	0.25	1.25	0.77	0.98
50	0.32	1.90	0.02	0.58	0.27	0.44
100	0.05	0.56	–0.05	0.15	0.03	0.11
200	0.01	0.05	–0.13	0.0	–0.10	0.0

shows this topology, and Table 6 summarizes the results for percentage change in Z_{in} and transmission phase. The via hole's proximity effects are similar to the cases discussed above.

Conclusion

The coupling effects between various lumped elements have shown that the effect on inductors is less than 1% for inductors having reactance of about 50 Ω and separated by 20 µm on a 75 µm thick GaAs substrate. Thus, a distance of 20 µm between lumped elements is safe for monolithic circuits at RF frequencies.

Table 5. Percentage change in the input impedance (Z_{in}) and transmission phase of an inductor due to grounded 10 pF MIM capacitor's close proximity.

Distance D (µm)	Re [ΔZ_{in}] Ω (%)		Im [ΔZ_{in}]Ω%		Δ[Ang.S_{21}]° (%)	
	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz
20	0.64	2.8	0.29	1.30	0.77	0.89
50	0.31	1.29	0.09	0.55	0.30	0.37
100	0.05	0.28	0.02	0.12	0.07	0.10
200	0.01	0.10	0.0	0.04	0.03	0.04

Table 6. Percentage change in the input impedance (Z_{in}) and transmission phase of an inductor due to via hole's close proximity.

Distance D (µm)	Re [ΔZ_{in}] Ω (%)		Im [ΔZ_{in}] Ω %		Δ[Ang.S_{21}]° (%)	
	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz	At 10 GHz	At 20 GHz
20	0.49	3.30	–0.60	1.80	0.0	1.12
50	0.21	1.81	–0.76	1.10	–0.44	0.63
100	0.15	0.96	–0.85	0.65	–0.64	0.35
200	0.06	0.65	–0.87	0.50	–0.71	0.26

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