On-Chip RF Transformer Performance Improvement Technique

Dr. Ahmed Saadoon Ezzulddin*, Dr. Mohammed Hussain Ali & Dr. Mutaz Shunasi Abdulwahab***

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Abstract

In this work, a proposed on-chip radio-frequency (RF) transformer design and layout technique is presented to achieve high magnetic coupling coefficient and low insertion loss by segmenting and interleaving wide primary and secondary metal traces. Additional advantage of such technique is the mitigation of proximity effect and current crowding. The proposed technique is verified and tested for a square transformer, with different segmentation structures, using EMSight simulator of Microwave Office 2007 (version 7.5) RF/Microwave software tools. By using this design and layout technique, the magnetic coupling coefficient improves from 0.49 to over 0.72 and lowers the minimum insertion loss from 1.56 dB to 1.18 dB at 4.5 GHz center frequency.

Keywords: on-chip RF transformer, square transformer, balun transformer, performance improvement technique, magnetic coupling coefficient, insertion loss, segmenting and interleaving wide metal traces.

تقنية لتحسين اداء المحولات راديوية التردد على الرقاقة

الخلاصة

في هذا البحث تم اقتراح تقنية لتصميم وتخطيط المحولات راديوية التردد علـــى الرقاقـــة لتحقيق معامل ترابط مغناطيسي عالي وخسائر ادراج واطئة عن طريق تجزئة وتداخل المسارات المعدنية الواسعة الابتدائية والثانوية. توفر هذه التقنية امكانية تخفيف تاثيرات المجاورة واختناقات التيارات. تم التحقق واختبار التقنية المقترحة على محولات مربعة الشكل لتراكيب تجزئة مختلفة باستخدام برنامج المحاكاة "EMSight" المتوفر مع الوسائل البرمجيـــة للتـــردات الراديويـــة والموجات الدقيقة "Microwave Office 2007" (الاصدار 7.5). باستخدام تقنية التصـــميم والتخطيط هذه تم تحسين معامل الترابط المغناطيسي من (0.49) الى اعلى من (0.72) وتخفيض خسائر الادراج الدنيا من (1.56 dB) الى (1.18 dB) عند تردد مركزي مقداره (4.5GHz).

* Electrical and Electronic Engineering Department, University of Technology/Baghdad.
** Laser and Optoelectronics Engineering Department, University of Technology/Baghdad.

Introduction

On-chip transformers contribute substantially in enhancing reliability, efficiency, and performance of silicon-integrated radio-frequency (RF) circuits. Recently, much research has focused on the design and characterization of integrated transformers. Transformers are typically used for impedance matching and conversion between differential and single-ended signals (balun operation), power combining, and tuning networks. Many researchers have reported the integration of on-chip transformers in power amplifiers (PAs), voltage-controlled oscillators (VCOs), and low-noise amplifiers (LNAs) [1].

By magnetically coupling two inductors, one can create a transformer, in which, the magnetic field created by the port-1 current I_1 through the primary inductor L_1 generates a voltage in the secondary inductor L_2. At the same time, the current through the secondary I_2 will magnetically induce a voltage in the primary circuit. The port voltages of the loosely coupled lossy transformer V_1 and V_2 in Figure 1(a) are related to their port currents through the following equations [2]:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_1 + jwL_1 & -jwM \\ jwM & -R_2 - jwL_2 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad \text{....(1)}$$

$$M = k\sqrt{L_1 . L_2} \quad \text{....(2)}$$

$$n = \sqrt{\frac{L_2}{L_1}} \approx \frac{I_1}{I_2} \approx \frac{V_2}{V_1} \quad \text{....(3)}$$

where M is the mutual inductance, k is the coupling factor, and n is the turn ratio between primary and secondary coils. Figure 1(b) shows the equivalent model for the transformer in Figure 1(a), where the lossy inductors of the transformer are modeled by the equivalent series resistors R_1 and R_2 and net inductances L_1 and L_2 for a single frequency. The quality factors Q_1 and Q_2, of the primary and the secondary inductors can be calculated in terms of R_1 and R_2, respectively, i.e. [2],

$$R_1 = \frac{wL_1}{Q_1} \text{ and } R_2 = \frac{wL_2}{Q_2} . \quad \text{...(4)}$$

Transformer Figure of Merit

In the case of a transformer, the main objective is the transfer of power from primary to secondary side. Thus the transformer efficiency (η_T) can be defined as the ratio of the output power (delivered to the load) to the input power. In view of the dependence of this ratio on the termination impedances, a more useful choice of figure of merit for RF transformers is the minimum insertion loss (IL_{min}) [3], which is defined as the inverse of the maximum available gain (G_{max}) and can be written as:

$$IL_{\min} = \frac{1}{G_{\max}} . \quad \text{....(5)}$$

The maximum available gain is defined by Ng *et al.* [4] and it has been used as a metric to measure the performance of transformers. G_{max} can be calculated using the following equations:

$$G_{\max} = h_{\max} = 1 + 2(x - \sqrt{x^2 + x}) = \frac{1}{1 + 2(x + \sqrt{x^2 + x})} \quad \text{...(6)}$$

$$x = \frac{1 - k_{\text{Re}}^2}{k_{\text{Im}}^2 Q_P Q_S + k_{\text{Re}}^2} \quad \text{.... (7)}$$

where η_{max} is a maximum efficiency of the transformer, and Q_P and Q_S are the quality factors of the primary and secondary coils.

$$Q_P = \frac{\mathrm{Im}(Z_{11})}{\mathrm{Re}(Z_{11})} \text{ and } Q_S = \frac{\mathrm{Im}(Z_{22})}{\mathrm{Re}(Z_{22})} \quad ..(8)$$

k_{Im} and k_{Re} are the imaginary and real terms of the mutual coupling factor:

$$k_{\mathrm{Im}} = \sqrt{\frac{\mathrm{Im}(Z_{12})\cdot \mathrm{Im}(Z_{21})}{\mathrm{Im}(Z_{11})\cdot \mathrm{Im}(Z_{22})}} \text{ and}$$

$$k_{\mathrm{Re}} = \sqrt{\frac{\mathrm{Re}(Z_{12})\cdot \mathrm{Re}(Z_{21})}{\mathrm{Re}(Z_{11})\cdot \mathrm{Re}(Z_{22})}}. \quad ...(9)$$

Equations (5), (6), and (7) express the minimum insertion loss of the transformer in terms of the quality factors of its primary and secondary coils and their mutual coupling.

In on-chip transformers, $k_{\mathrm{Re}}^2 << 1$ and $k_{\mathrm{Re}}^2 << k_{\mathrm{Im}}^2 Q_P Q_S$, equation (7) can be approximated as

$$x = 1/(k^2 Q_P Q_S) \quad ..(10)$$

where k is equal to k_{Im}.

Using equations (5), (6), and (10), the minimum insertion loss (IL_{min}) may be given, in dB, by

$$IL_{\min}(dB) = 10\log_{10}\left[1 + \frac{2}{k^2 Q_P Q_S} + 2\cdot\sqrt{\frac{1}{k^2 Q_P Q_S}\left(1+\frac{1}{k^2 Q_P Q_S}\right)}\right] \quad ..(11)$$

To obtain a minimum insertion loss (IL_{min}), the product of $k^2 Q_P Q_S$, in equation (11), needs to be maximized. The IL_{min} as a function of k and $Q=Q_P=Q_S$ is plotted in Figure 2. As shown in this figure, increasing the quality factors Q_P and Q_S or the mutual coupling factor k leads to a smaller IL_{min}. Therefore, an improvement of the minimum insertion loss can be achieved by an optimization of the quality factors of the transformer coils and the mutual coupling between them.

On-Chip Transformer Performance Improvement Techniques

Although on-chip transformers are more complicated than inductors, however, many of the techniques that have been applied to the optimization of inductors are also applicable to transformers, especially those methods used to improve the quality factor Q of the metal windings. There are several ways to improve Q. Some improvements can be made through the fabrication process, such as using thick copper top layers or strapping multiple levels of metal layers to reduce the ohmic losses; or using a thick oxide layer and/or high resistivity substrate (HRS) [5]; or even employing micromachining techniques [6]. Other improvements can be made through careful layout, such as using pattern ground shield (PGS) [7] to reduce the substrate loss induced by electrical fields.

Transformers make use of the magnetic coupling between the primary and secondary windings. Figure 3 shows the coupling coefficient k versus number of turns N, metal trace width W, and spacing s of the primary or secondary windings for a 1:1 Frlan transformer (see Figure 4). For the same width and spacing, there is a large improvement in k as N increases from 1 to 2, because of the coupling between adjacent lines. However, further increase in N does not improve k considerably. For the same N, k decreases when W and s increase. However, wider metal traces usually have better Q.

For some applications, such as the output transformers for PAs, the large

dc current requires wide metal traces for reliability. As illustrated previously, in Figure 2 and equation (11), to obtain a minimum insertion loss IL_{min}, the product of $k^2Q_pQ_s$ needs to be maximized. Hence, there must be an optimum metal width to balance k and Q for the maximum $k^2Q_pQ_s$.

The Proposed Technique to Improve Transformer Performance

Without altering the fabrication process, the wide metal traces can be split into multiple parallel segments and interleaved, as shown in Figure 5, in order to improve coupling coefficient, k. Another advantage is that the proximity effect and currant crowding are also mitigated. Because the effective width of the primary or secondary winding is enlarged, the self-inductances for the primary (L_p) and secondary (L_s) are reduced while the resistance remains about the same. So the quality factors for the primary (Q_p) and secondary (Q_s) will be reduced at low frequencies. The coupling capacitance between the primary and secondary windings increases. These contradictory effects need to be balanced in order to achieve an optimum minimum insertion loss (IL_{min}).

Simulation Results

To verify the feasibility of the segmentation idea in the transformer performance improvement, a square transformer with different segmentations is simulated using EMSight simulator. EMSight simulator is a 2.5-Dimension (2.5-D) electro-magnetic (EM) solver provided with Microwave Office (MWO) 2007 (version 7.5) RF/Microwave software tools from Applied Wave Research (AWR), Inc. [9]. It is based on an integral equation formulation of Maxwell's equations. It uses a volume mesh of conductors to handle layered dielectrics and substrates. It correctly accounts for sidewall capacitance, via resistance and inductance, and current crowding effects. EMSight simulator usually takes a long time, and a great deal of memory to simulate even simple structures. However, it can give relatively accurate results in a frequency range, as long as the simulation parameters are chosen correctly. So, it is useful as a validation tool when the geometry of the desired transformer is fixed. Moreover, given the high computation cost in EMSight simulation, it is not a good tool for optimization in the design process.

A summary of the important parameters for the transformer simulation process are listed in Table 1. Figure 6 shows an example of an EMSight setup for a 1:1 square transformer. Various transformer test structures, using the segmentation scheme and their simulation results are summarized in Table 2. If the outer dimension (D_{out}) is to be kept constant, the inductance (L) will decrease as the metal traces are split into more segments (T_1, T_2, T_3, and T_4). Alternatively, D_{out} will need to grow (T_5 and T_6) to achieve the same L of the basic transformer structure (T_1).

Figure 7 shows that for transformers T_1, T_2, T_3, and T_4 (with N_{seg} equal to 1, 2, 3, and 4, respectively), the quality factor (Q) decrease when N_{seg} increases. However, IL_{min} of transformer T_3 is about 0.44 dB less than IL_{min} of T_1 due to improvement in k. An IL_{min} as low as 1.12 dB can be achieved in

transformer T_3. For transformer T_4, although the segmentation scheme still improves k, the decrease of Q offsets the benefit, and the resulting IL_{min} is not effectively improved. Finally, Figure 7 shows a similar increase in k and decrease in Q_p, Q_s, and IL_{min} due to N_{seg} for transformer structures T_5 and T_6 (where N_{seg} equal to 2 and 3, respectively).

Conclusions

An on-chip transformer design and layout technique is proposed to achieve high magnetic coupling coefficient and thereby low-insertion loss, by segmenting and interleaving wide metal traces. Results have verified the proposed technique. In view of some practical issues of balun transformers, especially those used for RF PAs, it is deemed necessary to give special attention to their design to overcome any drawbacks. Usually a one-turn transformer is chosen for its better quality factor. Wide traces are used to meet the current density rules. Therefore, the magnetic coupling coefficient k is relatively small (around 0.5). It anticipated the transformers with traces segmented and interleaved, discussed in this work, can be used to improve k.

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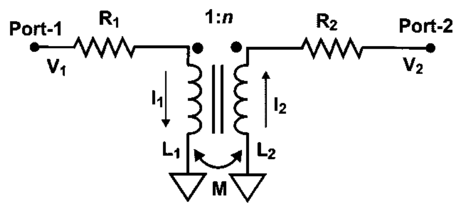
Table (1) Process technology parameters.

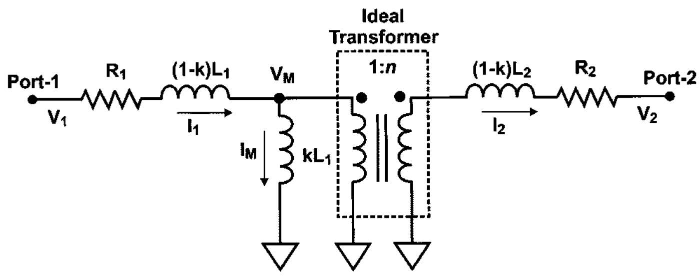
Process parameters	Value
Substrate thickness	200 μm
Substrate resistivity	10 Ω.cm
Silicon dielectric constant	11.9
Top metal (m6) thickness	2.0 μm
Second metal (m5) thickness	1.0 μm
Metal resistivity	0.027 Ω.μm
Oxide thickness (m6-substrate)	5.5 μm
Oxide thickness (m6-m5)	1.5 μm
SiO_2 dielectric constant	3.9

Table (2) Geometrical parameters and simulation results for the different transformer test structures T_1, T_2, T_3, T_4, T_5, and T_6 as defined in Figure 5.

Transformer	Geometrical parameters				Simulation results					
	N_{seg}	W_p, W_s (μm)	s (μm)	D_{out} (μm)	L_p (nH)	L_s (nH)	Peak Q_p	Peak Q_s	k	IL_{min} (dB)
T_1	1	24	2	300	0.66	0.55	10.87	11.73	0.49	1.56
T_2	2	12	2	300	0.51	0.48	10.63	11.38	0.67	1.18
T_3	3	8	2	300	0.46	0.45	10.44	11.13	0.72	1.12
T_4	4	6	2	300	0.43	0.43	10.21	10.87	0.74	1.11
T_5	2	12	2	332	0.64	0.56	10.26	10.90	0.67	1.22
T_6	3	8	2	348	0.63	0.57	9.93	10.46	0.72	1.18



(a)



(b)

Figure (1- a) Transformer model. (b) Transformer equivalent T-model [2].

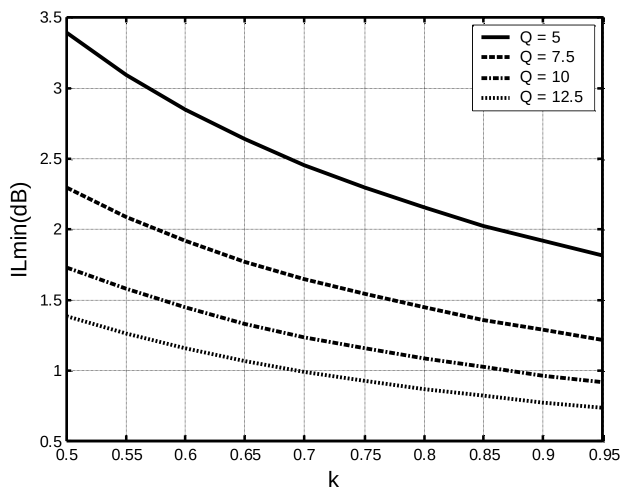


Figure (2) Minimum insertion loss IL_{min} versus coupling coefficient k for different of quality factor $Q = Q_P = Q_S$.

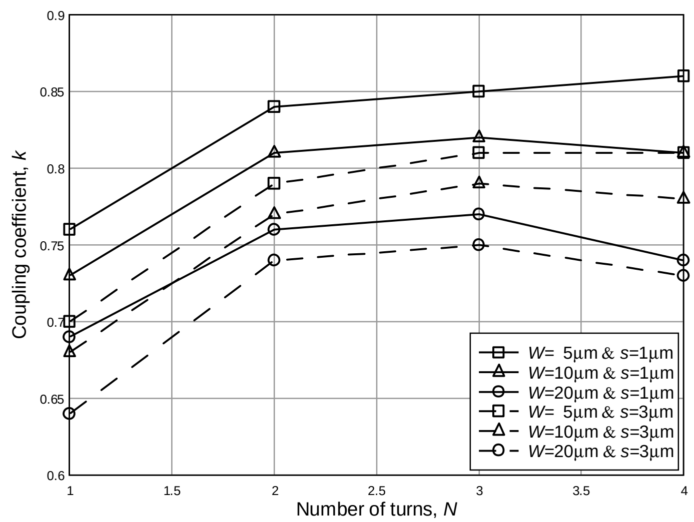


Figure (3) Coupling coefficient *k* versus number of turns $N=N_p=N_s$, metal trace width $W=W_p=W_s$, and spacing *s* for a 1:1 Frlan transformer with self-inductance $L=L_p=L_s$=5 nH [8].

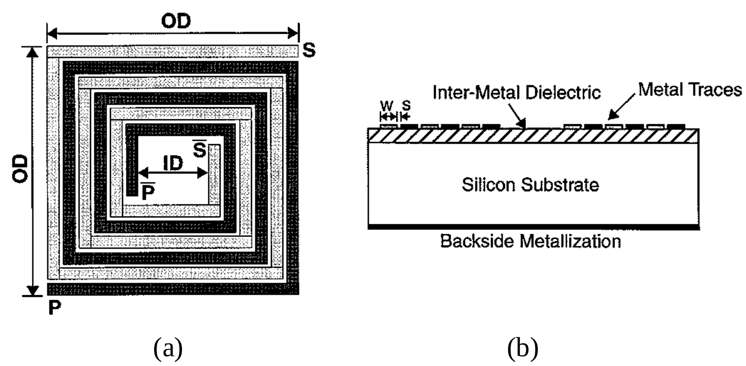
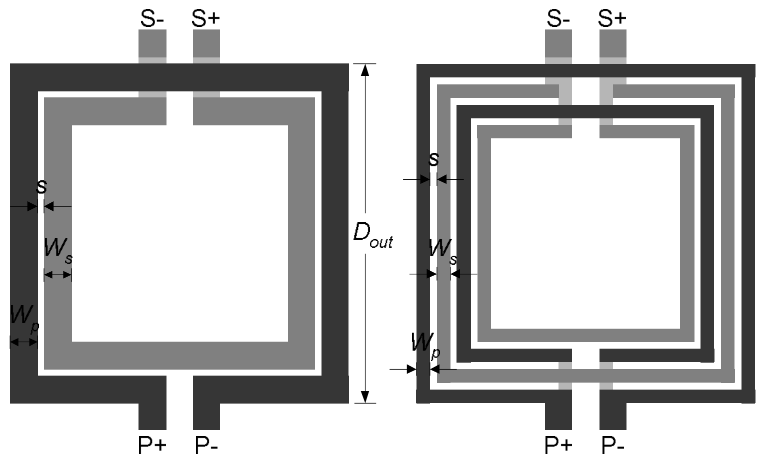
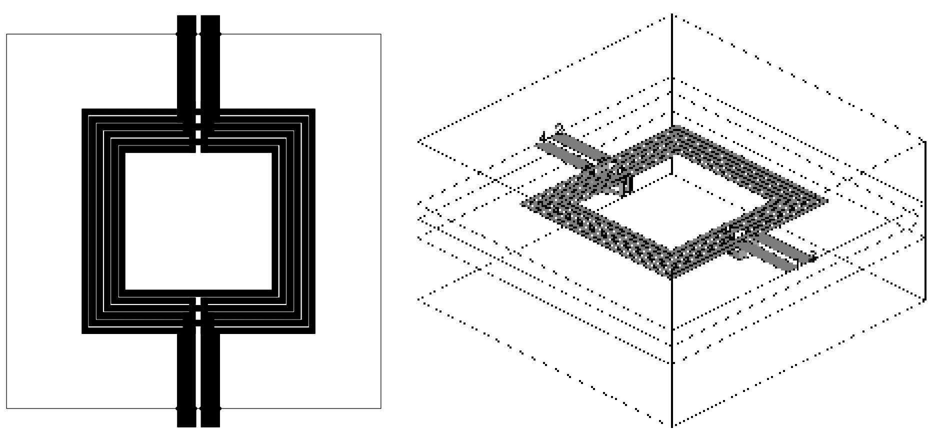


Figure (4) On-chip Frlan transformer (OD: outer dimension, ID: inner dimension, P: primary terminal, S: secondary terminal, W: metal trace width, and s: metal trace spacing,): (a) Top view, and (b) Cross-section [8].



(a) (b)

Figure (5 -a) A typical single-turn square transformer. (b) The same transformer with metal traces segmented and interleaved (number of segments N_{seg}=2).



(a) (b)

Figure (6) Example of EMSight setup for 1:1 square transformer with D_{out}=300 µm, W_p=W_s=8 µm, s=2 µm, and N_{seg}=3: (a) Top view, and (b) Perspective view.

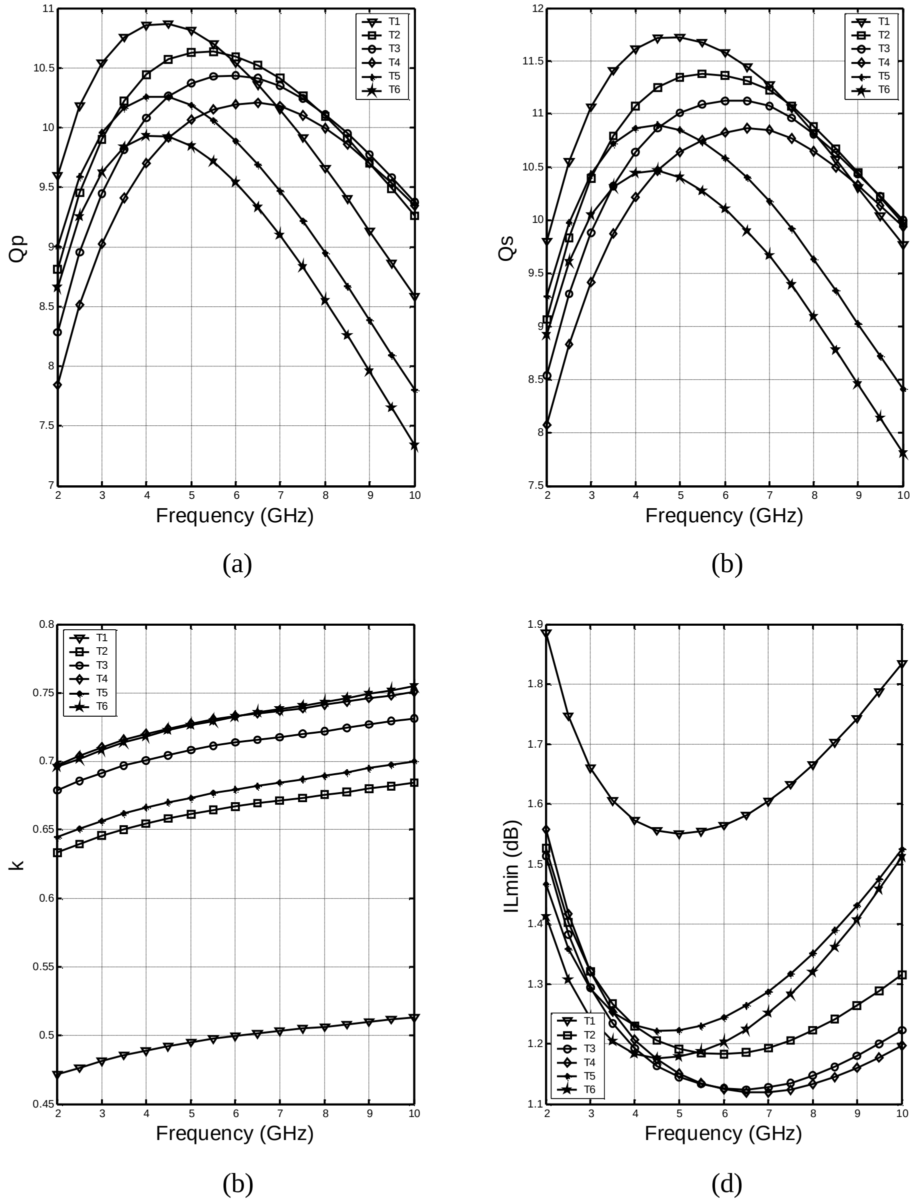


Figure (7) Simulation results and comparison of: (a) primary quality factor Q_p, (b) secondary quality factor Q_s, (c) coupling coefficient k, and (d) minimum insertion loss IL_{min} as a function of frequency for the different transformer test structures T_1, T_2, T_3, T_4, T_5, and T_6 in Table 2.