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# The Power Transfer Mechanism of MMIC Spiral Transformers and Adjacent Spiral Inductors

by

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**Abstract:**

With its accuracy verified by many tests, the software WATMIC-EMsim ([1], Part I)) is now used to analyze the coupling between (I) the two coils of an MMIC transformer and (II) two adjacent MMIC square spiral inductors. It is found that: (I) for the transformer, the simple magnetic coupling in power transfer between the two coils only occurs at the low frequency end of the microwave frequency, and (II) for the adjacent inductors, the coupling $S_{21}$ is very small. It begins at -26 dB when the two spirals nearly touch and rapidly drops as a function of $(1/d)^7$ where d is the center to center separation between the two spirals.

## Part I
## The Power Transfer of MMIC Spiral Transformers

### Introduction:

The classical (two coil) transformer has many uses in a low frequency circuit. The same may apply for the MMIC spiral transformer at microwave frequencies, provided that similarly efficient power transfer can be routinely designed.

To such end, the power transfer mechanism of the spiral transformer must be well understood. This paper is an attempt in this direction.

The understanding is achieved by analysing the current distribution of a spiral transformer example through the field theoretic software WATMIC-EMsim [1], The accuracy of the computed results is substantiated by experimental measurements on the actual spiral transformer.

### The responses of the Spiral Transformer as 2 and 4 Port Devices

Fig. 1 shows the spiral transformer example, including its surrounding brackets for "on wafer measurements" by coplanar probes.

As the influence of the brackets may not be negligible, for better agreement with the measurements therefore, the software WATMIC-EMsim computes the spiral transformer together with its surrounding bracket. The computed and measured scattering matrix responses of ports 1 and 2 plotted with excellent agreement.

A spiral transformer is basically a four port device. Fig. 1 shows the transformer in its two port configuration by grounding the other two ports, 3 and 4, on the brackets.

While not experimentally, numerically it is easy to convert the transformer-bracket configuration to a four port configuration by adding a 50 ohm series resistor to each of ports 3 and 4.

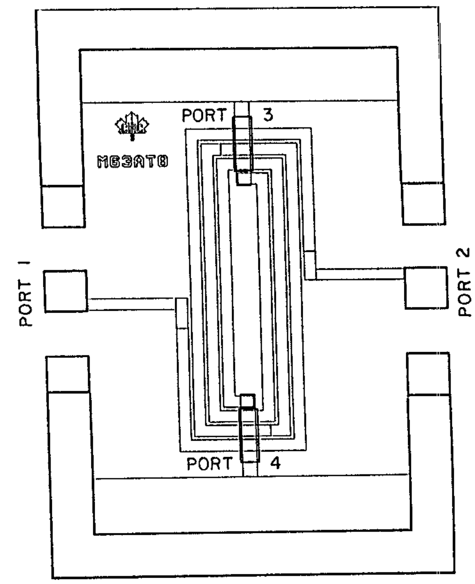


Fig. 1 The spiral transformer example.

The computed scattering matrix responses of ports 1 and 2 of the four port configuration are plotted in Fig. 3. The shapes of these responses agree well with those by Jansen [2].

### The Interpretation of the Responses and Power Transfer Mechanism

A comparison of the responses in Fig. 2 and 3 for the two and four port configurations, shows substantial differences. The $|S_{21}|$ and $|S_{11}|$ of the former show peaks and nulls while the pair of the latter show gradual increases with frequency. This can be explained by examining the current distributions along the spirals for both configurations.

The most important feature, may be the $|S_{21}|$ response of the <u>two</u> port configuration. There, in Fig. 2,. $|S_{21}|$ has a sharp null at 6 GHz. An examination of its current distribution shows that there is actually a nearly perfect $\lambda/4$ standing wave in the secondary spiral of the transformer, with maximum current in the grounded port 4 and <u>nearly zero</u> current in the output port 2. Thus, there is little power flowing into the load causing a null in $|S_{21}|$.



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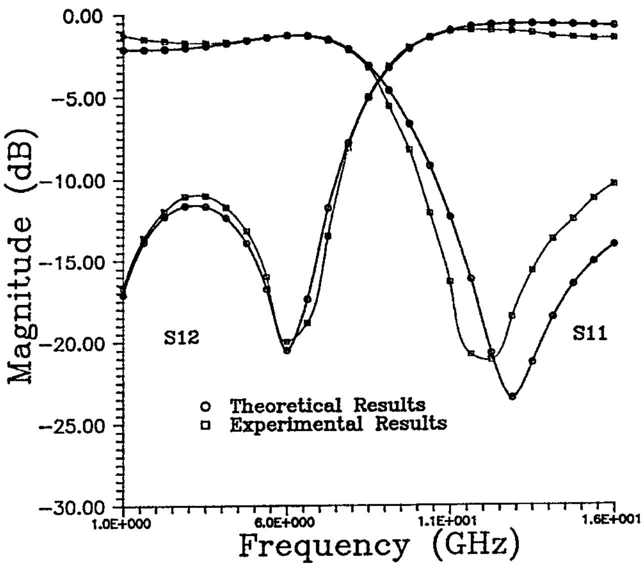



Fig. 2 The | $S_{21}$ | and | $S_{11}$ | responses of the two port configuration of the transformer in Fig. 1.

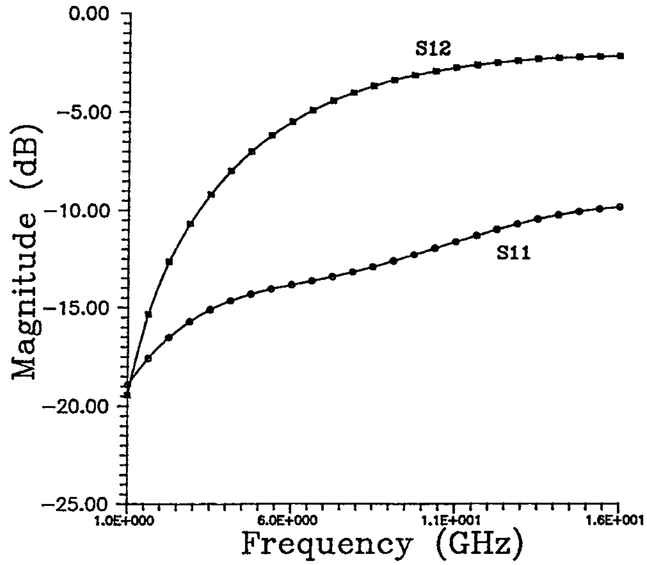



Fig. 3 The | $S_{21}$ | and | $S_{11}$ | responses of the four port configuration, constructed by adding 50 ohm series resistors to ports 3 and 4 in Fig. 1.

At frequencies below 6 GHz therefore, the current, in each of the electrically short spirals, is approximately constant. Therefore, like the classical transformer the power transfer is provided by magnetic coupling.

At frequencies above 6 GHz, the spirals are electrically long. Further, the current distribution along each spiral becomes less standing wave but more traveling wave, like a coupling transmission line. Therefore there is magnetic and electric coupling. The coupling is more complicated, however, since the transformer spirals wind into each other.

The | $S_{21}$ | response of the four port configuration, on the other hand, as shown in Fig. 3, has a smooth increase. The reason is that ports 3 and 4 in Fig 1 are not grounded but have the matched 50 ohm loads. Therefore there are no standing waves and the power transfer changes smoothly from the magnetic coupling to electric and magnetic coupling.

The smooth | $S_{21}$ | response pays a price of lower | $S_{21}$ | at high frequency due to the losses of the 50 matched loads in ports 3 and 4.

**The Necessary Conditions for Efficient Power Transfer**

The above results show that the most efficient power transfer is provided by the 2 port configuration of the transformer at high frequencies through both electric and magnetic coupling.

At such frequencies, however, each spiral is longer than $\lambda/4$. This may preclude the possibility of center tapping the secondary spiral to ground and obtaining a balanced output from ports 3 and 4.

At lower frequency, on the other hand, the transformer is in its classical magnetic coupling mode, and center tapping is possible. However, as observed in Fig. 2 at 3 GHz the power transfer | $S_{21}$ | is usually inefficient.

Based on the above observations and the knowledge of classical twin coil transformers, it appears that this latter problem can be overcome by (i) reducing the electrical length of the spiral at high frequency, i.e. raising the metallization above the substrate by pedestals to reduce the capacitances and thus increasing the propagation velocity along the spirals; and (ii) by increasing the number of turns of the spirals while maintaining the same spiral length. A way to achieve this is to have tighter transformer spirals.

**References**


1. EMsim: MIC software of EEsof Inc. Westlake Village, Ca. 1988. WATMIC: field theoretic software from Univ. of Waterloo, Waterloo, Ont., Canada 1987. WATMIC is embedded in EMsim.
2. R.H. Jansen, "LINMIC: a CAD package for the lay-out oriented design of single and multi layer MICS/MMICs up to mm-wave frequencies", Microwave Journal, vol. 29, No. 2, 1986; pp. 151-161.


## Part II
## The coupling of Adjacent Square Spiral Inductors

Twenty or more MMIC circuits have been accurately analyzed by the simple moment method software WATMIC [1][2][3][4], modified from the linear antenna formulation of Harrington [5]. The accuracy of WATMIC has been verified by comparison, some with the literature and mostly with experiments, in house [1][2][3] or from other workers [4].

With its accuracy verified, WATMIC is used to analyze the coupling of two identical square spiral inductors as shown in Fig. 1. The results of the analysis and their interpretations are important, since at the present time, there is little published information on the subject.

The even and odd input impedances of the two spiral inductors are given in Fig. 2. The gap between the two spirals is only 15 μm, corresponding to a center to center separation d of 425 μm in the two 410μm square spirals in Fig. 1. Even at such small gap, Fig. 2 shows that the even and odd mode split of resonant frequencies is less than ±1 GHz centering on 7.1 GHz. This can only mean that the coupling is very small.

Couplings is frequently measured by the transmission coefficient $S_{21}$. Fig. 3 shows the small coefficients $S_{21}$ for separations d of 425, 500 and 650 μm. The coefficient $S_{21}$ depends on frequency. It raises sharply from $-\infty$dB at dc but reaches a plateau at about 2 GHz. The plateau extends up to about 7.1 GHz, the resonant frequency of an isolated spiral.

The plateau levels $S_{21}$ are: -26.5 dB at d = 425 μm, -36 dB at d = 500 μm, and -50 dB at d = 650 μm. A plot of the plateau $S_{21}$ levels against the separations d shows that $S_{21}$ is proportional to $(1/d)^7$. This means that the coupling is decreasing very rapidly with separation of the spiral inductor.

The existence of the $S_{21}$ plateau against frequency, and the rapid decrease of the plateau levels against separation, can be easily interpreted.

A spiral inductor in free space is a magnetic dipole which has an H field proportional to $(1/d)^3$. In MMIC the spiral inductor has a negative image due to the ground plane. Together they form a quadrapole with the H field proportional to $(1/d)^4$. The coupling of this H field with the quadrapole of a second inductor with ground plane, gives the coupling $S_{21}$ proportional to $(1/d)^5$. With the addition of E field coupling, this coupling $S_{21}$becomes proportional to $(1/d)^7$.

The lumped circuit equivalent of the coupling spiral inductors is given in Fig. 4. When the L, C, R and the mutual M values numerically fitted with WATMIC results at 500 MHz, Fig. 3 shows excellent agreements up to 3 GHz, including the plateaus, of $S_{21}$ from the lumped circuit and WATMIC.

The mutual capacitance $C_m$ in Fig. 4 cannot be numerically fitted at 500 MHz and is neglected. This may account for the disagreement of the plateaus beyond 3 GHz.

The main conclusions of this paper are: (i) the coupling $S_{21}$ between MMIC spiral inductors is very small. It begins at -26.5 DB when the two spirals are nearly touched in Fig. 1, and rapidly drops to -50dB and below following $(1/d)^7$. (ii) the coupling $S_{21}$ remains a constant (i.e. a plateau) over a wide frequency range up to the resonant frequency of the spiral inductor.

Only square spiral inductors are computed by WATMIC presently. One expects a similarly small coupling for octagonal spiral inductors. This may be the reason why few MMIC designers have encountered difficulties traceable directly to the coupling of spiral inductors.

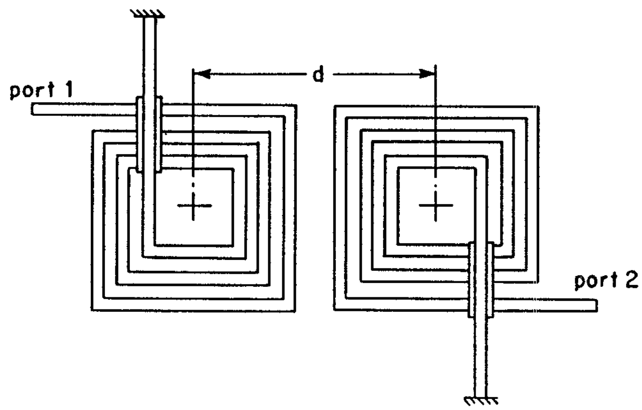



Fig. 1 Two coupled coils, $(410\ \mu m)^2$ each. Line width = 20 μm. Substrate h = 100 μm (GaAs), airbridge $h_{eff}$ = 4 μm (air).

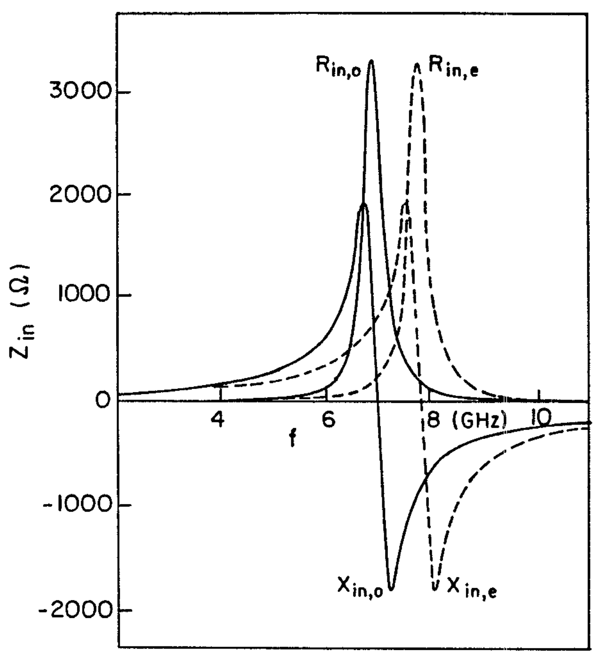



Fig. 2 The odd and even input impedances of the coupled coils, d = 425 μm.

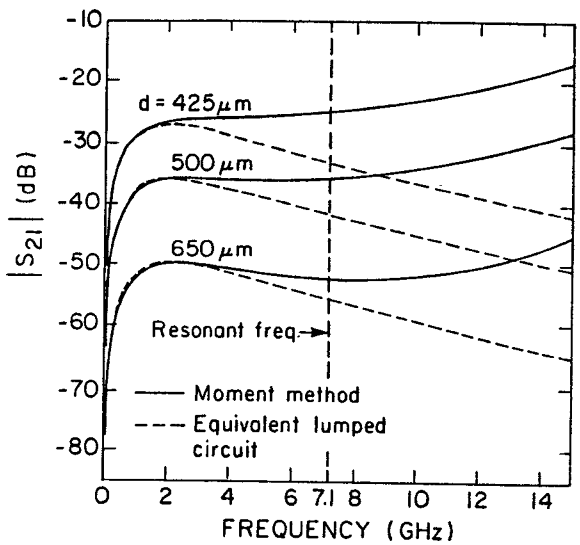
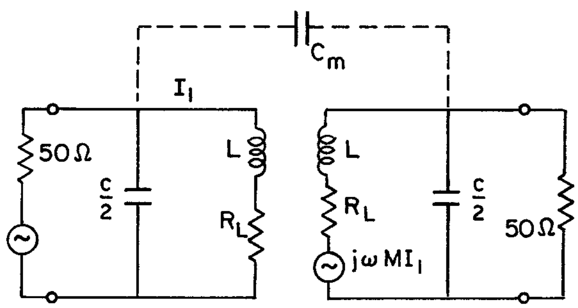



Fig. 3 The transfer loss of the coupled coils for several different distances.




| d(μm) | k |
|---|---|
| 425 | 0.04639 |
| 500 | 0.01655 |
| 650 | 0.003298 |

$L = 4.17$ nH

$M = kL$

$C = 0.24$ pF ($C_m = 0$)

$R_L = 7.34\ \Omega$

Fig. 4 The low frequency (500 MHz) equivalent circuit of the two coupled coils.

## References


[1] Y.L. Chow, X.Y. She, G. Howard, M.G. Stubbs and M. Gaudreault, "A modified moment method for the computation of complex MMIC circuits", Proc. Of the 16th European Microwave Conference, Dublin, Ireland, Sept. 1986, pp. 625-630.

[2] M.G. Stubbs, Y.L. Chow and G.E. Howard, "Use of a spatial field technique for the analysis of active MMICs", Proc. Of the 17th European Microwave Conference, Rome, Italy, Sept. 1987, pp. 273-278.

[3] G.E. Howard, "Analysis of passive and active microwave integrated circuits by the field approach", M.A.Sc. thesis, Dept. of Elect. Engrg., Univ. Of Waterloo, Waterloo, Ontario, Canada, February, 1988.

[4] Private communications with companies of EEsof, Avantek, Compact and Raytheon 1987-88.

[5] R.F. Harrington, "Field computation by moment methods", MacMillan Book Co., New York, 1968, pp. 62-81.