NEGATIVE COUPLING IN COMBLINE FILTERS

ELECTRICAL MODEL

Electrical circuit model of two coupled resonators, connected to 50 Ω ports is shown in Figure 1.

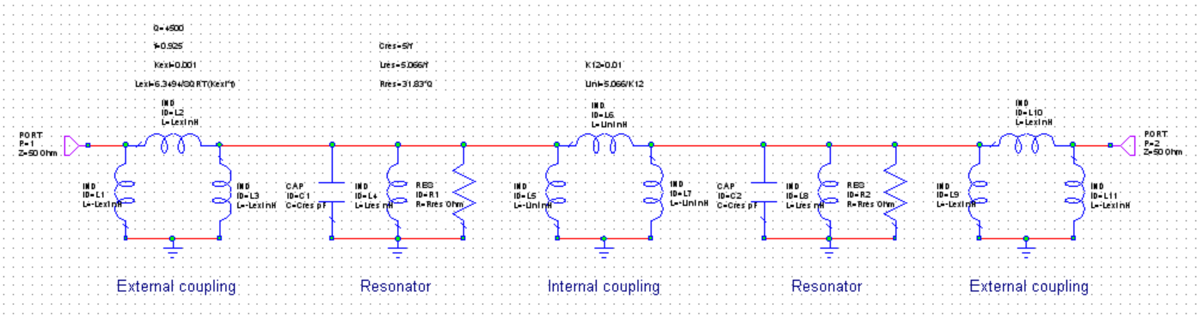


Figure 1

The internal and external coupling elements are both represented as inductive π networks. Resonators are modelled as parallel RLC circuits.

In the external coupler model, two shunt inductors have the value of $-L_{ext}$, while the series inductor has the value of L_{ext}, where

$$L_{\text{ext}} = \frac{6.35}{\sqrt{K_{\text{ext}} \cdot f}} \, [\text{nH}]$$

K_{ext} is the external coupling bandwidth in MHz, and f is the centre frequency in MHz. In the internal coupler model, two shunt inductors also have the value of $-L_{int}$, while the series inductor has the value of L_{int}, where

$$L_{\text{int}} = \frac{5.07}{K_{12}} \, [\text{nH}]$$

K_{12} is the required resonator-to-resonator coupling bandwidth in MHz. Resonator elements values can be calculated as:

$$C_{res} = \frac{5}{f} \, [\text{pF}]$$

$$L_{res} = \frac{5.07}{f} \, [\text{nH}]$$

$$R_{res} = 31.83 \cdot Q \, [\Omega]$$

where f is the centre (resonant) frequency in MHz and Q is the resonator quality factor. In this coupled resonator model, the resonator-to-resonator coupling bandwidth, K_{12}, can be either positive or negative. Negative coupling bandwidths are of special interest in cross-coupled filter topologies.

ELECTRICAL MODEL SIMULATED RESULTS

The simple filter model of Figure 1 is simulated with two sets of parameters, as shown in Table 1, where the only difference between the two sets is the sign of K_{12}:

Parameter	**Parameter Value Set 1 (POSITIVELY coupled resonators)**	**Parameter Value Set 2 (NEGATIVELY coupled resonators)**
Centre frequency, f_0	925 MHz	925 MHz
Resonator quality factor, Q	4,500	4,500
External coupling bandwidth, K_{ext}	1 MHz	1 MHz
Internal coupling bandwidth, K_{int}	10 MHz	-10 MHz

Table 1

Coupled resonator model of Figure 1 has been simulated with the two parameter sets shown in Table 1.

Figure 2 shows that:

- The reflected phase responses of the positively and negatively coupled resonators are identical.
- However, the transmitted phase responses are 180° out of phase:
  - Transmitted phase of POSITIVELY coupled resonators LEADS the reflected phase by 90°
  - Transmitted phase of NEGATIVELY coupled resonators LAGS the reflected phase by 90°

Figure 3 – Figure 5 show that the above observation is the only way that the sign of coupling between two resonators can be determined.

All magnitude-based measurements, such as s-parameters magnitude, and transmitted and reflected group delay, for the two circuits, one with K_{12} and the other one with $-K_{12}$, are identical.

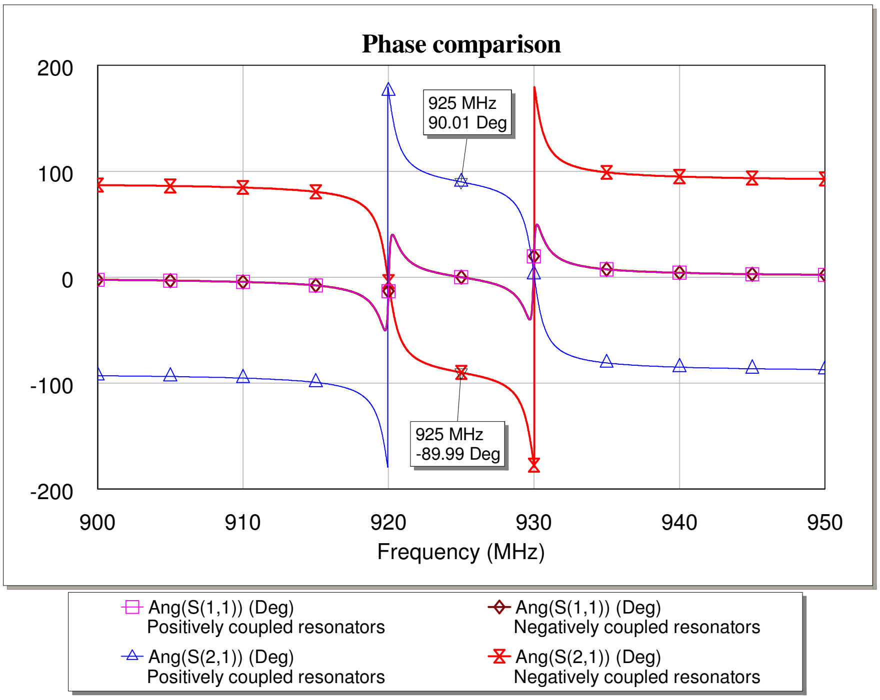


Figure 2

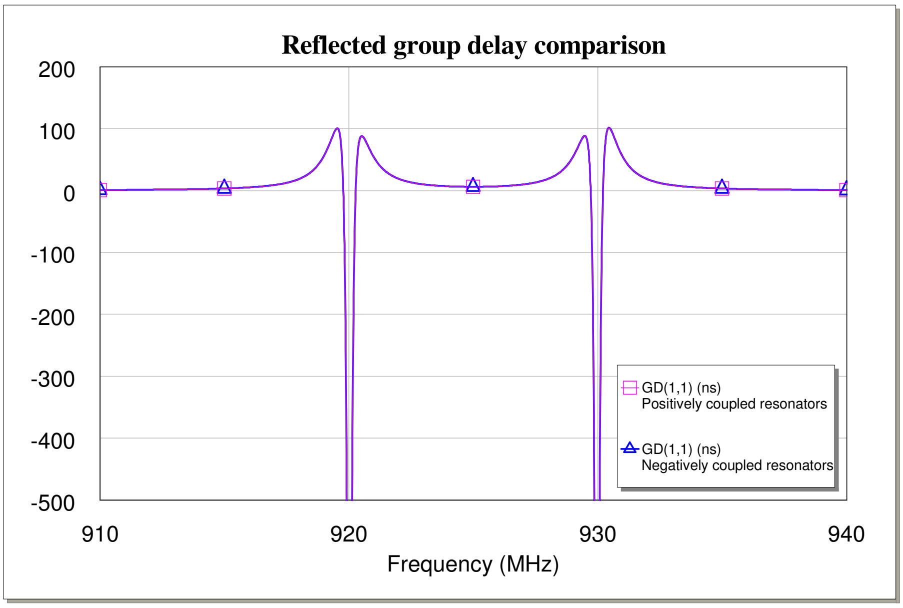


Figure 3

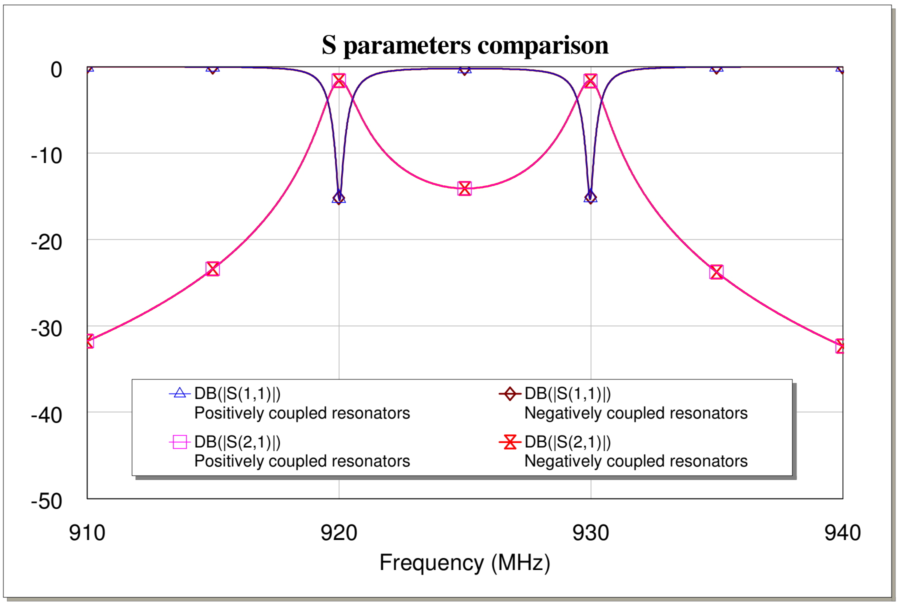


Figure 4

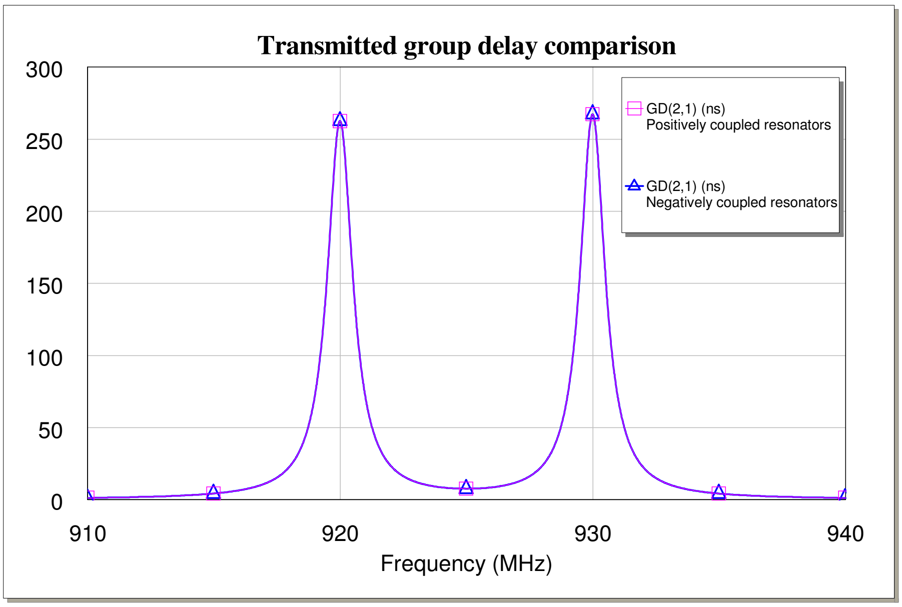


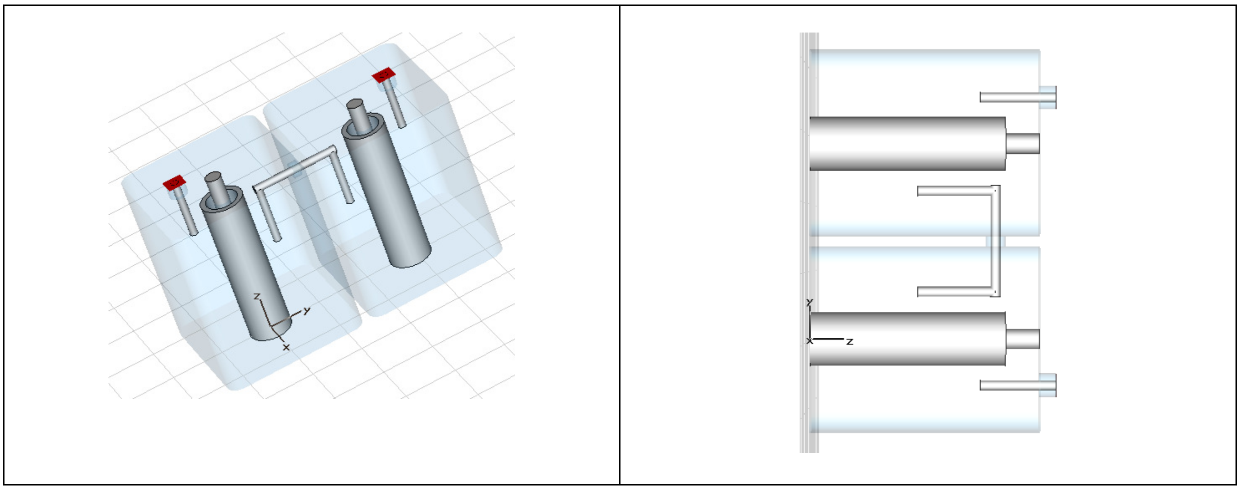
Figure 5

ELECTROMAGNETIC MODEL

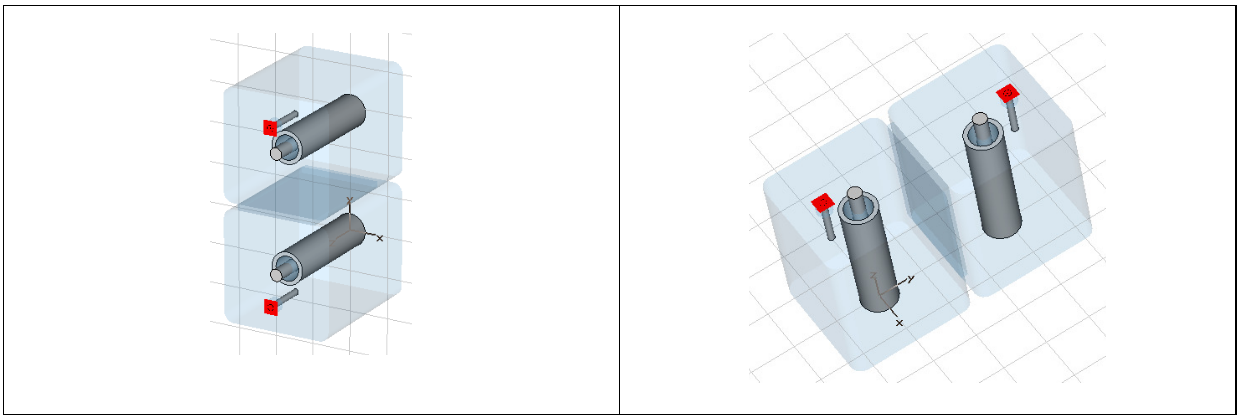
The result obtained on the basis of the electrical model can be verified by 3D electromagnetic simulation.

The following two structures were simulated in the 3D simulator:

- Two resonators coupled by an electric-field coupler (NEGATIVE)



- Two resonators coupled by a magnetic-field coupler (POSITIVE)



Exact dimensions of each of the two structures are shown in the Appendix.

SIMULATED RESULTS FROM THE ELECTROMAGNETIC MODEL

Simulated results shown in Figure 6 and Figure 7 confirm that:

- Transmitted phase is LAGGING the reflected phase for NEGATIVE coupling
    - -34.6 deg – (-124.6 deg) = 90 deg
- Transmitted phase is LEADING the reflected phase for POSITIVE coupling
    - 58.9 deg – (-31.1 deg) = 90 deg

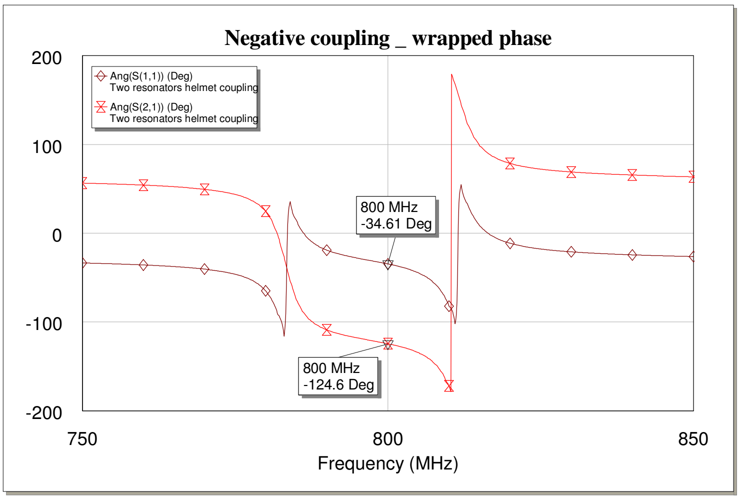


Figure 6

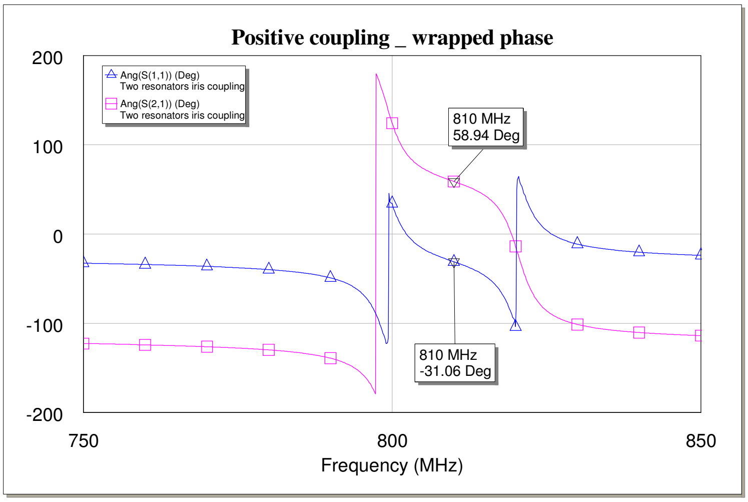


Figure 7

By observing the reflected and transmitted phases of the two structures, it is possible to determine the sign of the coupling. However, it is also useful to determine the absolute coupling bandwidth in each of the two cases.

POSITIVELY-COUPLED CASE

We first determine the external coupling bandwidth, by shorting one of the resonators, as shown in Figure 8. Only one port is used for simplicity (all energy is reflected back in any case).

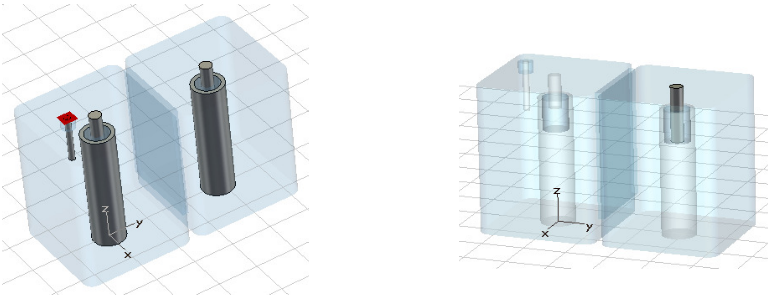


Figure 8

From the obtained reflected group delay response shown in Figure 9 it follows that the external coupling bandwidth is 5 MHz. Due to symmetry this refers both to Port 1 and Port 2.

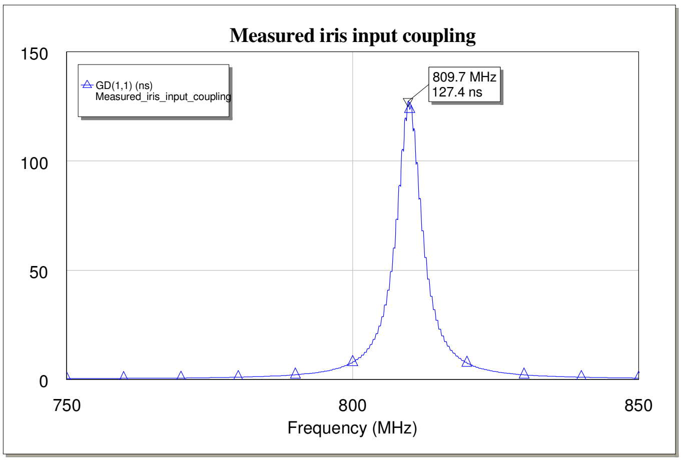


Figure 9

Next, we tune in the second resonator (previously shorted) to the centre frequency. From the reflected group delay response shown in Figure 10, we obtain resonator-to-resonator coupling bandwidth of K_{12} = 21.6 MHz.

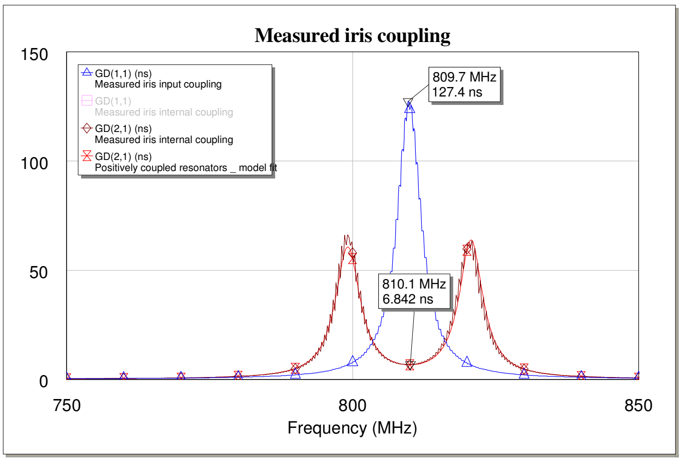


Figure 10

The structure is symmetric as the two screws have the same insertion into the two resonators. This means that each individual resonator is resonating at its nominal resonant frequency, but when coupled together, they shift about the centre frequency.

NEGATIVELY-COUPLED CASE

The same can be done in the case of the negatively coupled resonators. Figure 11 shows the reflected group delay response with the first resonator tuned in (the second one is shorted), and Figure 12 shows the response with both resonator tuned in to the centre frequency.

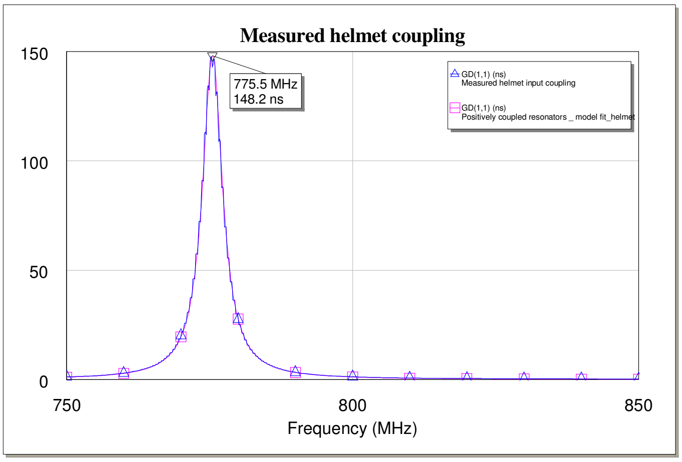


Figure 11

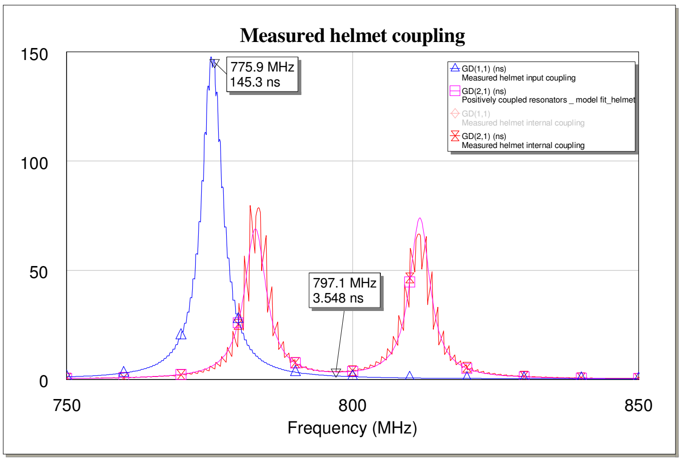


Figure 12

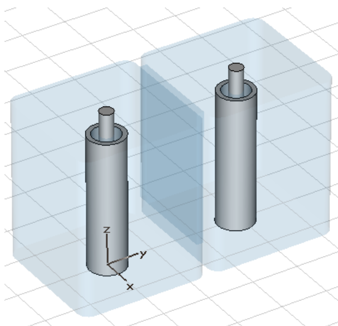
From the reflected group delay responses we obtain the external coupling bandwidth of K_{ext} = 4.3 MHz and resonator-to-resonator coupling bandwidth of K_{12} = 27.7 MHz.

In both structures we substituted the extracted coupling bandwidths and used them in the electrical coupled resonator model of Figure 1. Both Figure 11 and Figure 12 show good agreement between the coupled resonator circuit results produced by the electrical model and with the 3D electromagnetic model.

RESULTS VERIFICATION

In the previous section, coupling bandwidths were calculated by using a frequency-domain solver. Here we confirm that the same bandwidths are obtained with an eigenmode solver.

With positive iris coupling, as shown below, the following modes are obtained:



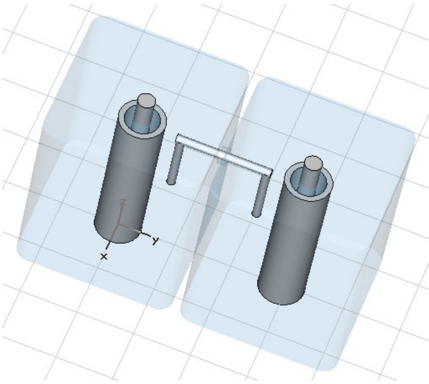
Mode1 = 835.6 MHz

Mode2= 857.2 MHz

Mode3 = 2501 MHz

From here the coupling bandwidth can be calculated as K_{12} = Mode2 – Mode1 = 21.6 MHz, which is exactly the same as calculated previously.

The following eigenmodes are obtained in the case negative coupling:



Mode1 = DC

Mode2 = 797.6 MHz

Mode3 = 827.8 MHz

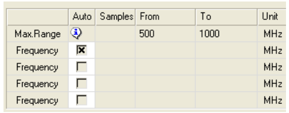
Mode4 = 1889 MHz

Resonator-to-resonator coupling bandwidth is calculated as Mode3 – Mode2 = 827.8 MHz – 797.6 MHz = 30.2 MHz. Unless there is an unnoticed parameter difference, the small difference compared to the result obtained with the frequency-domain solver is due to resonator loading.

APPENDIX

ELECTROMAGNETIC STRUCTURE PARAMETERS

Parameter	Value	Structure	Parameter	Value
cavdia	55	M, E	Mesh type	hexahedral
cavlen	68	M, E	Lines per wavelength	20
cavrad	5	M, E	Lower mesh limit	20
cbdia	12	M, E	Mesh line ratio limit	10
cblen	15	M, E	M: Nx, Ny, Nz	39, 77, 41
holedia	6	E	E: Nx, Ny, Nz	37, 85, 40
holehei	55	E	M: Meshcells	115,520
irisbre	3	M, E	E: Meshcells	117,936
irislen	58	M	Solver method	Resonant: Fast S-Parameter
iriswid	40	M	Solver settings	NOT Store result data in cache NOT Calculate modes only Accuracy (hexahedral mesh) = 1e-6
pin1len	22.5	E	Resonant Solver settings	Eval. Freq. 750 (default) Samples = 1001

pindia	3	M, E	Normalize to fixed impedance	50 Ω
port1offset	cavdia/4	M, E	Frequency samples	
port2len	22.5	E	Adaptive mesh refinement	NOT Adaptive hexahedral mesh refinement
port1pinlen	22.5	M	Distributed Computing	NOT Run remote calculation
port2offset	cavdia/4	M, E		
port2pinlen	22.5	M		
portdia	7	E		
portoffset	cavdia/4	M		
portpindia	3	M		
resdia	16	M, E		
reslen	58	M, E		
spacing	58	M, E		
tsdia	6	M, E		
tseln2	15	M, E		
tslen	15	M, E		
wire1len	23	E		
wiredia	3	E		
wirelen	30	E		

ELECTROMAGNETIC SIMULATION PORT RESULTS

	PORT 1 & PORT2	PORT 1 & PORT 2	PORT 1 & PORT 2	PORT 1 & PORT 2
Type	E-Field (peak)	E-Field (peak)	H-Field (peak)	H-Field (peak)
Mode type	TEM	TEM	TEM	TEM
Accuracy	2.71112e-14	2.2882e-14	2.71112e-14	2.2882e-14
Beta	20.9585 1/m	15.7188 1/m	20.9585 1/m	15.7188 1/m
Wave Imp.	376.73 Ohms	376.73 Ohms	376.73 Ohms	376.73 Ohms
Line Imp.	47.4827 Ohms	47.4827 Ohms	47.4827 Ohms	47.4827 Ohms
Plane at z	73	73	73	73
Frequency	1000	750	1000	750
Phase	0 degrees	0 degrees	0 degrees	0
Maximum-2d	4901.04 V/m	4901.04 V/m	14.3003 A/m	14.3003 A/m

VERSION HISTORY

Version 1 (18 MARCH 2009): First release