phase difference between the excitations without coupling and with coupling.

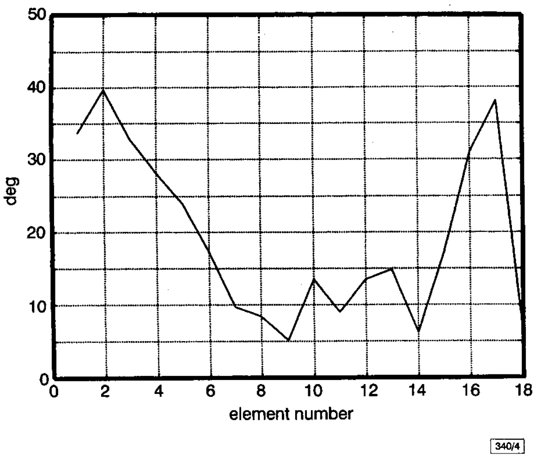


**Fig. 4** *Change in excitation due to mutual coupling*

*Conclusions:* The mutual coupling computed with a hybrid UTD-MoM model was used in a simulation for a circular array of 18 rectangular aperture elements. The coupling data had previously been verified against measurements. Our analysis shows that the mutual coupling has a strong effect on the radiation pattern, especially for a shaped beam. It is necessary to include a model for the mutual coupling in the synthesis procedure; a simple method for achieving this has been described.


25 February 1999
*Electronics Letters Online No: 19990395*
*DOI: 10.1049/el:19990395*

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**References**


1 BUCCI, O., FRANCESCHETTI, G., MAZZARELLA, G., and PANARIELLO, G.: 'Intersection approach to array pattern synthesis', *IEE Proc. H*, 1990, **137**, pp. 349–357
2 VASKELAINEN, L.I.: 'Iterative least-squares synthesis methods for conformal array antennas with optimized polarization and frequency properties', *IEEE Trans.*, 1997, **AP-245**, (7), pp. 1179–1185
3 PATHAK, P.H., and WANG, N.: 'Ray analysis of mutual coupling between antennas on a convex surface', *IEEE Trans.*, 1981, **AP-29**, (6), pp. 911–922
4 PERSSON, P., and JOSEFSSON, L.: 'Mutual coupling effects in conformal arrays'. Proc. EMB 98, Linköping, Sweden, November 1998, pp. 124–131


## Design of rectangular directional coupler using simple numerical algorithm

J.H. Yun, J.W. Lee and J.S. Chae

A simple numerical algorithm for the design of a rectangular directional coupler (RDC) with arbitrary couplings is proposed. The performance of a designed RDC is also described. It is seen that the measured data agree well with the results predicted by using the proposed algorithm.

*Introduction:* In this Letter we describe a simple numerical algorithm for designing rectangular directional couplers (RDCs) which is useful for EMC testing over a broadband frequency range, with high input/output power. The RDC presented in this Letter was developed based on the concept of an expanded coupled transmission line (CTL) cell which the authors have recently proposed [1]. It consists of a rectangular outer conductor tapered at both ends and two inner conductors located inside the coupler as shown in Fig. 1. Each inner conductor is connected to the 50Ω coaxial cable. The odd mode characteristic impedance $Z_{0o}$ of the CTL cell must be maintained at 50Ω [1]. However, the characteristic impedance $Z_O$ (= $\sqrt{[Z_{0o}Z_{0e}]}$, where $Z_{0e}$ is the even mode characteristic impedance) of the RDC must be maintained at 50Ω. Moreover, we have to design the RDC for the given $Z_{0o}$ and $Z_{0e}$ (or coupling $C$ and $Z_O$). When the values of $d$, $h$, and $b$ in Fig. 1*c* are given, a numerical algorithm for determining the $a$ and $w$ which satisfy the arbitrary couplings is presented in this Letter. As a field enclosure, the RDC works in TEM mode from DC to the cutoff frequency at which the first higher mode appears.

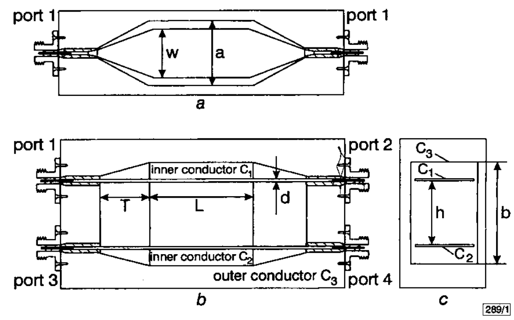


**Fig. 1** *Structure of rectangular directional coupler*

*a* Plane view of RDC
*b* Front view of RDC
*c* Cross-section of RDC

*Extended NRM mixed with MM:* A combination of the NRM (Newton Raphson method) with the MM (moment method) [1, 2] is useful for the design of impedance matching structures for coaxial transmission lines. We can easily calculate an unknown variable under one condition by using this combination of the NRM with MM [1, 2]. In this Letter, we introduce an extension of the NRM combined with MM to determine two unknown variables under two conditions.

The procedure of the algorithm for the design of the RDC is as follows:

(i) The charge distribution on the contour of the RDC is calculated by the MM from the quasi-static charge integral equation (QSCIE) [3].

(ii) $Z_{0o}$ and $Z_{0e}$ are evaluated from the results of charge distribution.

(iii) Two variables ($a$ and $w$ in Fig. 1) for the structure satisfied by constants $Z_{0o}$ and $Z_{0e}$ are found using the NRM for systems [4]. This algorithm is simply described as:

$$w_n = w_{n-1} - \left\{ \frac{(Z_{0o}(\rho)-Z_{0o})\frac{\partial}{\partial a}(Z_{0e}(\rho)) - (Z_{0e}(\rho)-Z_{0e})\frac{\partial}{\partial a}(Z_{0o}(\rho))}{\frac{\partial}{\partial w}(Z_{0o}(\rho))\frac{\partial}{\partial a}(Z_{0e}(\rho)) - \frac{\partial}{\partial a}(Z_{0o}(\rho))\frac{\partial}{\partial w}(Z_{0e}(\rho))} \right\}_{\substack{w=w_{n-1} \\ a=a_{n-1}}} \quad (1)$$

$$a_n = a_{n-1} - \left\{ \frac{(Z_{0e}(\rho)-Z_{0e})\frac{\partial}{\partial w}(Z_{0o}(\rho)) - (Z_{0o}(\rho)-Z_{0o})\frac{\partial}{\partial w}(Z_{0e}(\rho))}{\frac{\partial}{\partial w}(Z_{0o}(\rho))\frac{\partial}{\partial a}(Z_{0e}(\rho)) - \frac{\partial}{\partial a}(Z_{0o}(\rho))\frac{\partial}{\partial w}(Z_{0e}(\rho))} \right\}_{\substack{w=w_{n-1} \\ a=a_{n-1}}} \quad (2)$$

$$Z_{0o}(\rho) = \frac{\eta_0 V_1}{\varepsilon_0 \int_{c_1} \rho dc_1'} \quad \text{for } V_1 = V \text{ [V] and } V_2 = -V \text{ [V]} \quad (3)$$

$$Z_{0e}(\rho) = \frac{\eta_0 V_1}{\varepsilon_0 \int_{c_1} \rho dc_1'} \quad \text{for } V_1 = V \text{ [V] and } V_2 = V \text{ [V]} \quad (4)$$

$$\rho = \sum_{i=1}^{N} \alpha_i B_i(c') \quad (5)$$

$$[\alpha_i] = [g_j][Z_{ij}]^{-1} \quad (6)$$

$$z_{ij} = \left\langle W_j(c), \frac{1}{2\pi} \int_{c_1+c_2+c_3} B_i(c') \ln\left\{ \frac{1}{\sqrt{(x-x')^2 + (y-y')^2}} \right\} dc' \right\rangle \quad (7)$$

$$g_j = \langle W_j(c), V(c) \rangle \quad (8)$$

where $c'$ is a source point and $c$ is an observation point on the contour ($C_1$, $C_2$, and $C_3$ in Fig. 1*c*). $B_i(c')$, $W_i(c)$ and ρ are the basis function, weight function, and charge on contours, respectively. $V_1$ and $V_2$ are input voltages on $C_1$ and $C_2$.

*Experimental results of designed RDC:* The 50Ω RDC with maximum coupling 30dB ($Z_{0o}$ = 48.443Ω and $Z_{0o}$ = 51.607Ω [5]) and centre frequency 1000MHz has been designed using the extended NRM combined with the MM. The basis and weight functions of the MM are pulse and delta functions, respectively. We could design an RDC structure with 30dB when the iterative number was 4, as shown in Table 1. The total number of elements is 140. The calculated $w$ and $a$ are 2.956 and 4.898cm when $b$, $h$ and $d$ are 7.5, 4.5 and 0.5cm, respectively. Here, $L$ is 7.5cm due to the centre frequency of 1000MHz and $T$ is 2.0cm.

**Table 1**: Numerical results for designing structure of 30dB RDC

| Iterative number $n$ | Calculated results | | Characteristic impedance of odd mode ($Z_{0o}$) | Characteristic impedance of even mode ($Z_{0e}$) |
|---|---|---|---|---|
| | Width of outer conductor ($a$) | Width of inner conductor ($w$) | | |
| | cm | cm | Ω | Ω |
| 1 | 4.200 | 2.5000 | 51.2522 | 53.3684 |
| 2 | 4.9086 | 2.9662 | 48.3582 | 51.5335 |
| 3 | 4.8982 | 2.9565 | 48.4432 | 51.6070 |
| 4 | 4.8983 | 2.9565 | 48.4431 | 51.6069 |

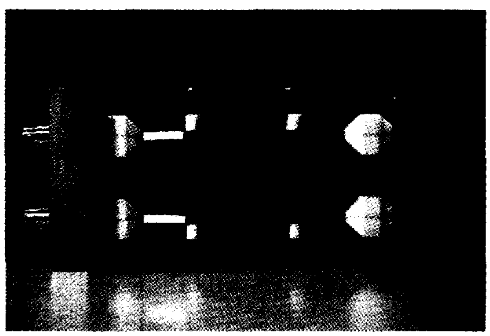

**Fig. 2** *Photograph of designed RDC, with opened outer conductor*

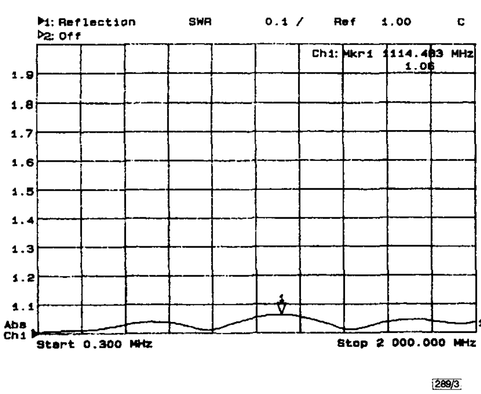


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**Fig. 3** *Input VSWR at port 1 of designed RDC*

Fig. 2 shows a photograph of the designed RDC, the outer conductor of which is opened. The input VSWR at port 1 of the designed RDC against frequency is shown in Fig. 3. The VSWR at port 2 has been omitted because it gives almost the same result. The VSWR at each input port is less than 1.06 for frequencies up to 2GHz. Using Galerkin method programmes [6], we can easily determine that the first cutoff frequency ($TE_{01}$ mode) is 1.834GHz and the second cutoff frequency ($TE_{10}$ mode) is 2.0GHz (calculated result of $TE_{10}$ by the waveguide formula [7]: 2.0GHz). In the detailed design, the frequency range is restricted up to the first cutoff frequency because of the QSCIE in the numerical algorithm.

Fig. 4 depicts the measured coupling and isolation. The flatness of the designed RDC between 500MHz and 1.2GHz is within ±1dB. We can see that the designed RDC has very good impedance matching and broadband characteristics.

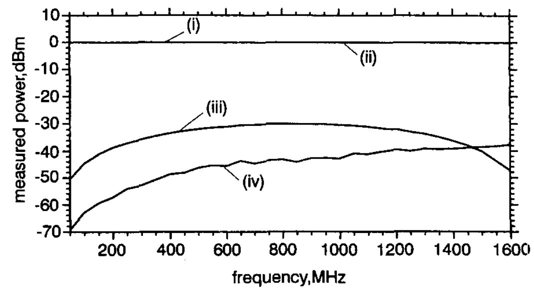


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**Fig. 4** *Measured coupling and isolation of designed RDC*

(i) input power
(ii) output power
(iii) coupled power
(iv) isolated power

*Conclusion:* A rectangular directional coupler (RDC) has been designed by using an extension of the NRM combined with the MM. The designed RDC has good performance with the VSWR < 1.06 below the cutoff frequency at which a higher order mode begins to propagate. The predicted coupling and impedance of the RDC agree well with the experimental results. We can see that the numerical algorithm is very useful for designing RDCs with arbitrary coupling.


5 February 1999
*Electronics Letters Online No: 19990472*
*DOI: 10.1049/el:19990472*

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## References

1 YUN, J.H., KIM, J.S., KIM, W.S., and KIM, J.K.: 'Performance of coupled transmission line cell for generating standard EM fields', *Electron. Lett.*, 1998, **34**, (12), pp. 1210–1211

2 YUN, J.H., and KIM, J.K.: 'Circular TEM cell for generating standard electromagnetic field', *Electron. Lett.*, 1997, **33**, (22), pp. 1853–1854

3 SPIEGEL, R.J., JOINES, W.T., BLACKMAN, C.F., and WOOD, A.W.: 'A method for calculating electric and magnetic fields in TEM cells at ELF', *IEEE Trans.*, 1987, **EMC-29**, (4), pp. 262–272

4 FAIRES, J.D., and BURDEN, R.L.: 'Numerical method' (PWS Publishing Company, 1993), pp. 346–351

5 POZAR, D.M.: 'Microwave engineering' (Addison-Wesley Publishing Company, 1990), pp. 421–430

6 YUN, J.H., LEE, H.J., and KIM, J.K.: 'Numerical solution of higher order mode cutoff frequencies in asymmetric TEM cells by Galerkin method', to be published in *IEEE Trans. EMC*, 1998

7 WEIL, C.M., and GRUNER, L.: 'Higher order mode cutoff in rectangular striplines', *IEEE Trans.*, 1984, **MTT-32**, pp. 638–641