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OPTIMUM SYNTHESIS OF SYMMETRICAL BRANCH-WAVEGUIDE DIRECTIONAL COUPLERS

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ABSTRACT

An optimised synthesis procedure to design branch-waveguide directional couplers for satellite beam forming network applications is reported. This procedure allows to achieve a very significant improvement, particularly for the input reflection and isolation, also for couplers with few branches.

A 5-branch 3 dB coupler, designed with the described method, has been manufactured in WR75 waveguide.

Comparing scattering parameter measurements with the computed frequency performance shows that the synthesis procedure is verified very satisfactorily.

Return loss and isolation values are 40 dB minimum on a 15% bandwidth.

The computer package allows also to calculate the sensitivity of the electrical characteristics versus geometrical parameters and then enables to evaluate the tolerances required for the mechanical manufacturing.

Moreover theoretical results of a 7-branch 3 dB coupler with wide frequency band (11.7-14.5 GHz) are presented.

INTRODUCTION

The growth of satellite communications requires antennae with shaped beams and multibeams which can be obtained with single or double reflector antenna systems fed by beam forming networks (BFN).

The directional coupler is a widely used component in BFN's and should have the following characteristics (Fig. 1):

a) minimum size, then minimum number of branches;
b) equal length (1) for all branches, that simplifies the mechanical realization;
c) minimum value for the input reflection and high isolation.

A directional coupler with all branches of equal length is the symmetrical branch-waveguide coupler proposed by Reed [1] many years ago. The present paper, starting from the Reed model, introduces a new method of synthesis which allows:

1) better matching between the computed and experimental values of the coupling on the operation frequency band;
2) a reduction of the number of branches under the same conditions of input reflection and isolation.

In the synthesis proposed in this paper the problem 1) is solved by changing the ideal equivalent circuit of the E-plane T-junction used by Reed, with an exact rapresentation of the electromagnetic discontinuity obtained with a mode-matching technique [2] [7].

The problem 2) is solved by an optimisation technique that, maintaining the device symmetry, allows the modification of the geometric dimensions of the coupler. In this way it is possible to obtain very low values of the input reflection and high isolation maintaining the required coupling value with a reduced number of branches.

The computed and experimental results, obtained on couplers designed with this optimised technique allow to evaluate the remarkable improvement achieved particularly for the input reflection and isolation. It is to be enphasized that the coupler electrical performance has been obtained without any sort of experimental trimming.

Finally sensitivity calculations versus geometrical parameters are given in order to define mechanical tolerances in the coupler manufacturing.

DESIGN PROCEDURE

In the theory proposed by Reed [1], the symmetrical branch-waveguide coupler, shown in Fig. 1, is designed neglecting the discontinuity effects in each E-plane T-junction.

In this work instead the fringing field effects in each T-junction are considered. The exact parameter values of the equivalent circuit of the T-junction, shown in Fig. 2, have been optained with a mode-matching technique [2]. This equivalent circuit has the same shape of the Marcuvitz circuit [3] but the parameter values differ from those of ref. [3].

Using the equivalent circuit of the T-junction and according to ref. [7], it is possible to obtain the following new design-formulae (see Figs. 1÷2).

a) Inner branches:

$$y = \frac{X/Z_0}{n^2 b'_c/b} \qquad (1)$$

$$lc = \frac{\lambda g_0}{2\pi} \operatorname{arccot}(y) - 2\, d'c \qquad (2)$$

$$\frac{b_c}{b} = \frac{n^2 b'_c/b}{\sin[\operatorname{arccot}(y)]} \qquad (3)$$

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$$S'_c = \frac{\lambda go}{4} + 2\ d_c - b'_c \qquad (4)$$

b) External branches:

$$y' = \frac{X/Z_o}{n^2 b'_i/b} \qquad (5)$$

$$li = \frac{\lambda go}{2\pi}\ \text{arccot}(y') - 2\ d'i \qquad (6)$$

$$\frac{b_i}{b} = \frac{n^2 b'_i/b}{\sin[\text{arccot}(y')]} \qquad (7)$$

$$S'_i = \frac{\lambda go}{4} + d_c + d_i - \frac{b'_c}{2} - \frac{b'_i}{2} \qquad (8)$$

where:

b_i, b_c : are the geometrical dimensions obtained from Reed theory;

X, n, d_i, d'_i, d_c, d'_c : are the T-junction parameters [2], functions of b'/b and λgo;

S'_c, S'_i, l_i, l_c, b'_i, b'_c: are the new geometrical dimensions of the coupler;

λgo : is the waveguide wavelength at the midband frequency.

From eq. (3) and (7) the correct values for b'_c and b'_i are achieved.

From eq. (2) and (6) l_c and l_i can be directly derived and then eq. (4) and (8) supply S'_c and S'_i.

In order to use the coupler in the BFN it is better to have equal length for all branches. Then we chose a lenght l as average of l_i and l_c. This involves a small asymmetry of the coupling frequency response, that however can be corrected by optimisation.

To develop the analysis algorithm that allows to calculate the frequency response of the coupler, we used the method shown in [6] because of the symmetry of the device.

With this first correction of the Reed theory the frequency responses for coupling and insertion loss are satisfactory enough. But in order to obtain an acceptable value of input reflection and isolation (>35 dB) we should use couplers with 8 branches. The reduction of the number of branches is obtained with the optimisation technique.

The analysis algorithm, the first building block of the optimisation method, is done on the model shown in Fig. 3 [6]. The calculations are carried out by dividing the coupler in sections (see Fig. 3) and evaluating the ABCD matrix of each section of course taking the parameters of the T-junction equivalent circuit into account. Then with easy matrix products we obtain the chain matrix of the whole model of Fig. 3.

Afterwards the ABCD matrix is converted into scattering parameters [4] and finally [6] the frequency response of the whole coupler is achieved.

The core of the optimisation algorithm makes use of a multivariable pattern search [5] in which the dimensions b'_i, b'_c, S'_i, S'_c of the various sections and l (see Fig. 1) are the variables.

However it must be borne in mind that the coupler symmetry reduces the number of variables by two.

The second building block of the optimisation method is the objective function which is done so as to allow:

a) minimisation of input reflection and maximization of the isolation;
b) adjustment of the coupling value;
c) adjustment of the mid-frequency.

The objective function, that is to be minimized, turns out to be the following:

$$F = \sum_{n=1}^{N} \left(\left| I_{ro} \right| + S_{11n} \right)^2 + \left(I_{so} + S_{41n} \right)^2 + \left[\alpha \left(\left| C_o \right| + S_{31n} \right) \right]^2 \qquad (9)$$

where:

I_{ro}, I_{so}, C_o : are the required values (in dB) for: input reflection, isolation and coupling;

S_{11n}, S_{41n}, S_{31n}: are the scattering parameters (in dB) calculated at the n-frequency point;

N : is the number of frequency points in which the device response is calculated;

α : is a constant.

A good value for α is 50 and N can be chosen between 15-20 depending of the coupler bandwidth.

The first two terms of F are not taken into account if $|I_{ro}| + S_{11n} < 0$ and $I_{so} + S_{41n} < 0$.

Because a loss-free structure is assumed the forward transmission is related to the above scattering coefficients via the unitary condition and can therefore be disregarded in defining F.

The starting point is the result obtained from the design formulae 1-8.

At the end of the optimisation the coupler, maintaining the symmetry, has the inner sections (see Fig. 3) no more identical as in the Reed synthesis (see Fig. 1); however every branch has the same length.

The rapid convergence of the optimisation algorithm allows to use only a desk calculator.

DESIGN EXAMPLES AND EXPERIMENTAL RESULTS

The design technique described above has been successfully employed to design and manufacture a 5-branch 3 dB coupler in WR75 waveguide with 10.95-12.75 GHz bandwidth.

Figs. 4 and 5 show the calculated frequency response of input reflection coefficient and isolation before and after the optimisation process and the experimental performance.

From these results the great improvement obtained can be evaluate.

From Figs. 6 and 7 that give the coupling and the forward transmission the adjustment of the mid-frequency is well proved. As it can be seen the asymmetry of the coupling frequency response has been removed by the l parameter optimization.

The measured coupling value is about 0.2 dB lower than the theoretical one. Also a 4.4 dB coupler has been realized and the experimental coupling showed the same error of 0.2 dB. This can be imputed to the electromagnetic model used that does not take the losses into account.

Finally Fig. 8 shows the considerable improvement obtained with the optimisation algorithm in the phase shift between coupled and direct ports.

A remarkable thing is that the experimental results are obtained without the necessity of any trimming. That demonstrated the capabilities of the proposed method to design directional couplers with the desired values of coupling, isolation and reflection.

Moreover the possibility of designing a coupler with a wide operating frequency band has been investigated. Such kind of couplers can be usefully utilized when the same BFN is used for both up and down links.

Figs. 9-11 show the frequency response of a 7-branch 3 dB coupler in WR75 with the smaller dimension dropped of 50%. The coupler bandwidth is 11.7-14.5 GHz. This kind of waveguide allows to improve the flatness of the coupling in the operating frequency bandwidth.

The experimental results are not yet available.

SENSITIVITY

These calculations have been done to achieve a better knowledge of how critical are geometrical dimensions of the coupler.

The same analysis algorithm shown above has been used.

The sensitivity has been carried out, assuming as a reference the frequency response of the optimised prototype shown in Fig. 4-8, for a certain variation of a single parameter. In this way the geometrical parameter maximum variation that does not appreciably change the frequency response of the coupler can be obtained.

Then the worst case is controlled setting the value of every variation maximum and with the same sign.

The mechanical tolerances of the 3 dB coupler prototype have been defined in this way and they are reported in Tab. 1.

These mechanical tolerances can be considered suitable for designing directional couplers in the 10-15 GHz frequency band.

DIMENSIONS (see Fig. 3)	TOLERANCES (mm)
b_1	±0.02
b_2	±0.03
b_3	±0.04
S_1	±0.05
S_2	±0.05
l	±0.1

Tab.1 - 5-branch 3dB coupler. Mechanical tolerances

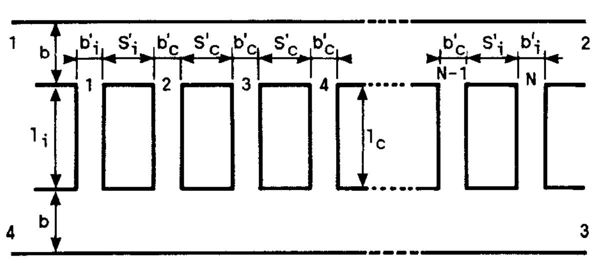

Fig.1 - Cross section of the directional coupler

CONCLUSIONS

The optimised synthesis technique for branch-waveguide directional couplers gives superior results, particularly for the input reflection and the isolation, compared with the previous methods, also for couplers with a reduced number of branches.

The measured results for pratical branch-waveguide couplers agree with the computed results and the performance of the device designed with the presented method seems very suitable not only for beam forming networks but even for general applications.

Finally, using the same analysis algorithm, the mechanical tolerances of the coupler manufacturing have been calculated.

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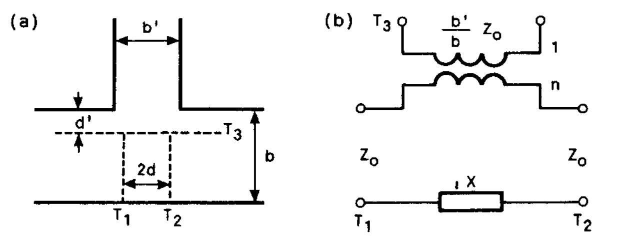

Fig.2 - a) E-plane T-junction; b) Equivalent circuit

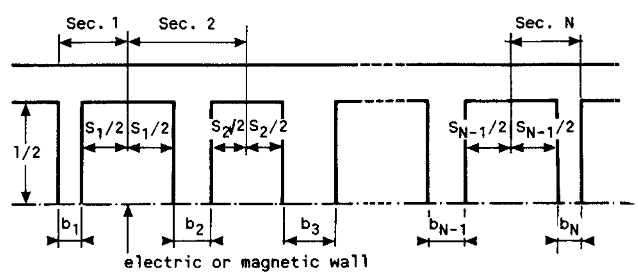

Fig.3 - Division of the coupler in sections. For maintaining the device symmetry must be: Sec.2=Sec N-1 and so on

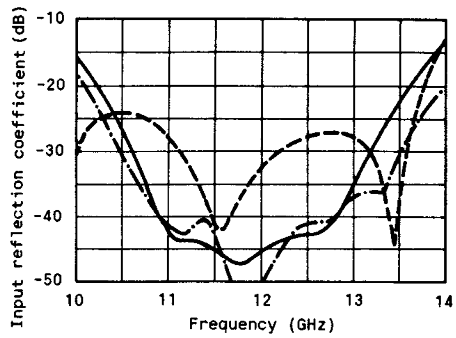

Fig.4 - 5-branch 3 dB coupler. Input reflection coefficient
Theory: _ _ _ before optim.; _____ after
Exper.: _._._

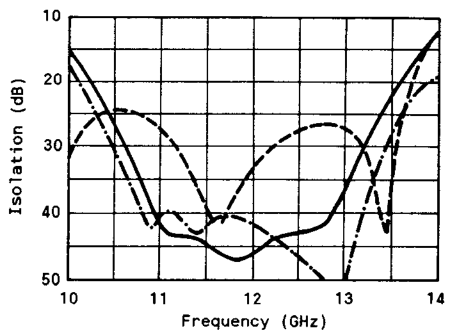

Fig.5 - 5-branch 3 dB coupler. Isolation
Theory: _ _ _ before optim.; _____ after
Exper.: _._._

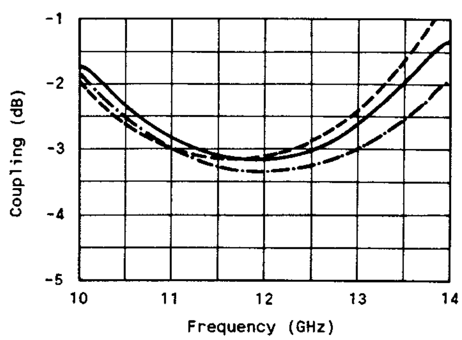

Fig.6 - 5-branch 3 dB coupler. Coupling
Theory: _ _ _ before optim.; _____ after
Exper.: _._._

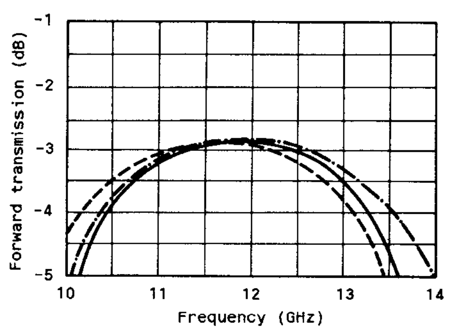

Fig.7 - 5-branch 3dB coupler. Forward transmission
Theory: _ _ _ before optim.; _____ after
Exper.: _._._

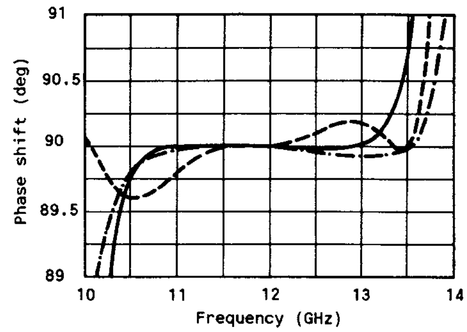

Fig.8 - 5-branch 3 dB coupler. Phase shift
Theory: _ _ _ before optim.; _____ after
Exper.: _._._

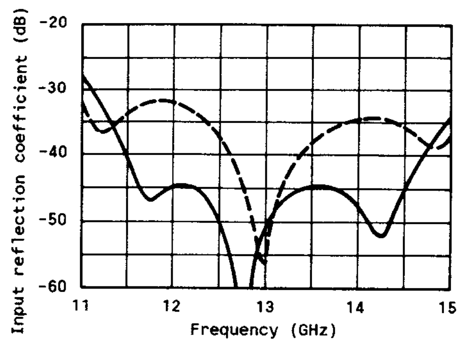

Fig.9 - 7-branch 3 dB coupler. Input reflection coefficient
Theory: _ _ _ before optim.; _____ after

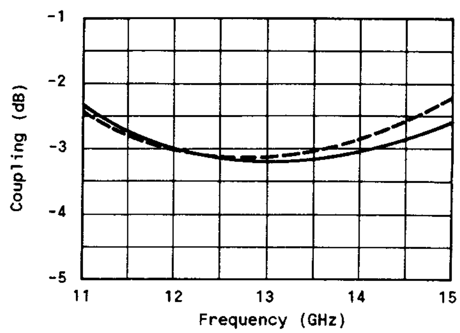

Fig.10 - 7-branch 3 dB coupler. Coupling
Theory: _ _ _ before optim.; _____ after

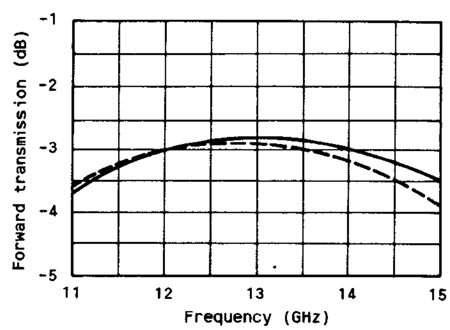

Fig.11 - 7-branch 3dB coupler. Forward transmission
Theory: _ _ _ before optim.; _____ after