WAVEGUIDE DIRECTIONAL COUPLERS FOR HIGH RF POWER DISTRIBUTION

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Abstract

Accelerator rf systems need rf high power dividers. Conventionally power is distributed by Magic Tees to 2^n acceleration structures in tree like waveguide systems. As an alternative, directional couplers can be used in a line like distribution system for any number of acceleration structures with less total waveguide length and less need for installation space. However this system needs different coupling ratios. The subject of this report is to show how a standard given waveguide directional coupler can be easily changed to any wanted coupling value under conditions of match at all ports and high directivity.

Introduction

The high rf power distribution system of HERA is a 500 MHz waveguide system. It uses mainly waveguide directional couplers as power dividers. Fig.1 shows the HERA rf system which is installed for 16 superconducting cavities. Cryostats and cavities will complete this system about the end of 1990.

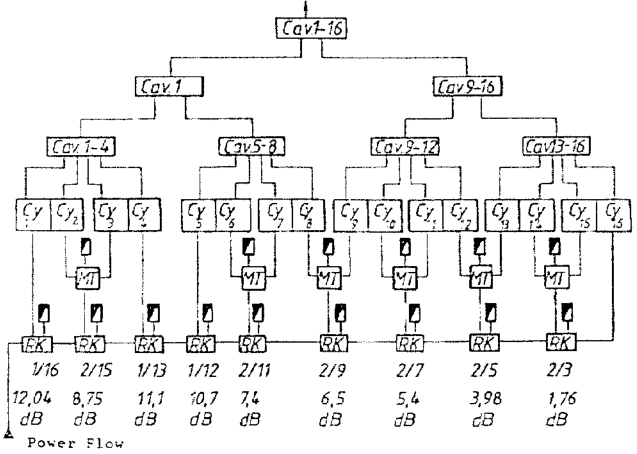

Fig.1: HERA SC Cavities, RF System Schematically

The upper part of Fig.1 shows the fundamental mode pick up lines and the combining system to win an overall sum of accelerating voltages. Cy1..16 symbolize cavities and cryostats. On the lower part of the picture Rk is a symbol for waveguide directional couplers connected by WR 1800 waveguide. The numbers below the symbols give their coupling ratio directly and in dB. In between the line of directional couplers and cryostats the MT stands for 3 dB power splitters -Magic Tees- . This mixed arrangement fits best into the limited space of the HERA tunnel. The advantage of saving space by a line distribution on the other hand leads to many different coupling values. The requirement for equality of power for each one of the 16 cavities results in a coupling ratio of 1/16 for the first cavity nearest to the transmitter. Supply of the next two cavities needs 2/15 of the remaining power etc. Needing many different coupling values makes it interesting to have one standard unit which is easily changeable to any coupling value. Subject of the following considerations are basic theory and practical results of how to realize this.

Fig.2 shows a coupler of the type which will be treated. It has 4 symmetrical ports. The maximum interaction of the two coupled lines is determined by the length of missing wall between them and can be reduced by bars or even plungers in between. These should meet the symmetry requirement. In practice it proves to be relatively easy to realize coupling ratios empirically by changing number or positions of the bars, but after this manipulation the coupler is no longer a directional coupler. Normally the ports are mismatched and the directivity is very low. Empirically finding proper compensations for the mismatches and reestablishing high directivity at the same time proved to be too difficult. This is the problem to be solved with the help of some theory.

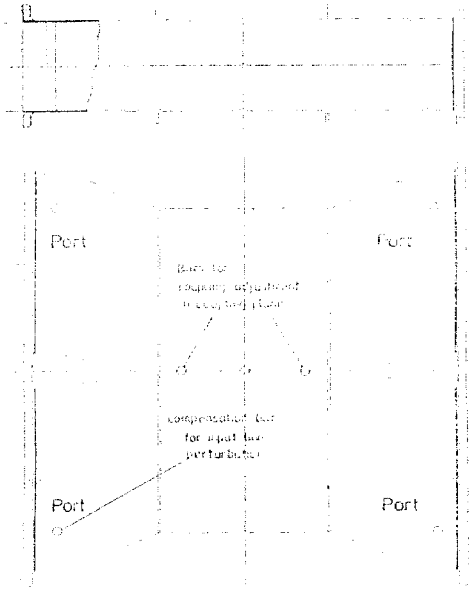

Fig.2: Standard Waveguide Directional Coupler

Lossless General Symmetrical 4-port

A general symmetrical 4-port which is characterized by the symmetry features of Fig.2 may be described by a scattering matrix (S_{ij}) representation [1] like

$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} S11 & S12 & S13 & S14 \\ S12 & S11 & S14 & S13 \\ S13 & S14 & S11 & S12 \\ S14 & S13 & S12 & S11 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \qquad (1)$$

If A .. D are the input signals at the 4 ports then a .. d are the reflected signals. With S_1, S_2, S_3, S_4 being the complex column vectors of (S_{ij}) and * symbolizing conjugate complex values there are 4 following additional equations valid.

$$S_1 S_1^* = 1 \; ; \; S_1 S_2^* = 0 \; ; \; S_1 S_3^* = 0 \; ; \; S_1 S_4^* = 0 \qquad (2)$$

Equations (2) yield 4 independant real equations for the complex scattering parameters S11 .. S14. Fixing for example real and imaginary parts of S11, S12 consequently determines also S13,S14. This means, that generally a symmetrical 4-port device like a mismatched coupler with very bad directivity is given by only 4 independant parameters. Hence there is no big step to the hypothesis that this coupler generally can also be described by an ideal directional coupler with equal pieces of a perturbed line attached to every port. Fig. 3 shows this structured set up. The intention of the following investigations is to show that the hypothesis is true and to find relations between the S-paramaters of the general symmetrical 4-port and the characteristic data of an electrically equivalent replacement set up of the type of Fig.3.
Thus the electrical position and the amount of a perturbing shunt impedance as well as the source of low directivity can be found.

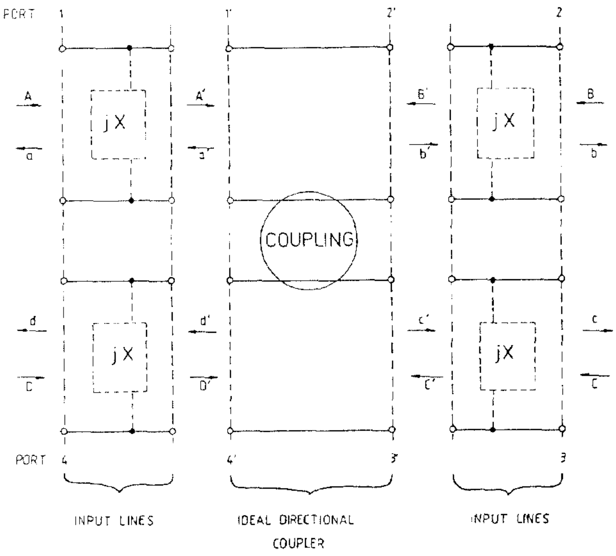

Fig.3: Symmetrical 4-Port (Lossless)

Analysis of Structured Replacement set up

S-parameters S11..S14 can be measured. This can be done by terminating ports 1 .. 4 by their waveimpedance, supplying power of voltage A=1 to port 1 only and measuring reflection a and signals b,c,d relating their phases to the input signal. Reflected signals B..D will be zero because of matched lines condition. Signals a .. d are the S-parameters S11 .. S14. Any of the 4 ports could be port 1 beause of symmetry.
A first step to relate the measured S-parameters to the components' characteristics of Fig.3 is a description of the components' behaviour.

The ideal directional coupler of Fig.3 is characterized by equ. (1) with a..d, A..D replaced by the signals a'..d', A'..D'at ports 1'..4'. It's S11 equals zero because measurement of S-parameters -like described above - would yield a'=0 at port 1' due to match. If ports 2' and 3' are the coupled ports then S14 also is zero, because the directivity is infinity. Expressing S12, S13 by their polar coordinates and applying equations (2) yields generally for the ideal coupler

$$\begin{aligned} &S11 = 0 && ; \; S12 = (S, \Psi 2) \; ; \\ &S13 = (s, \Psi 2 \pm \pi/2) && ; \; S14 = 0 \qquad (3) \\ &s \; = \sqrt{(1 - S^2)} && \end{aligned}$$

The second component of Fig.3 is a perturbed piece of line like shown in Fig.4. It can be described also by a scattering matrix representation.

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} L11 & L12 \\ L12 & L22 \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} \qquad (4)$$

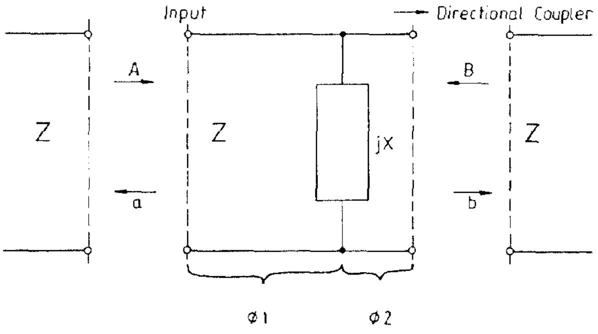

Fig.4: Perturbed Piece of Line

The matrix unity condition of equ. (2) changes with L_1,L_2 being the column vectors to

$$L_1 L_1^* = 1 \; ; \; L_2 L_2^* = 1 \; ; \; L_1 L_2^* = 0 \quad . \qquad (5)$$

In polar coordinates these equations are fulfilled [1] by

$$\begin{aligned} &L11 = (r, \Phi 1) \; ; \; L22 = (r, \Phi 2) \; ; \\ &L12 = (\sqrt{(1 - r^2)}, (\Phi 1 + \Phi 2 \pm \pi)/2) \quad . \qquad (6) \end{aligned}$$

A useful consequence for the following considerations is

$$L11L22 - L12^2 = (1, \Phi 1 + \Phi 2) \quad . \qquad (6a)$$

The actual relations to the circuit of Fig.4 are found to be

$$\begin{aligned} &|X| = \sqrt{((1 - r^2)/(4r^2))} \; ; \qquad (7) \\ &\Phi 1 = -2\varnothing 1 \pm \pi - \arctan(2X) \; ; \Phi 2 = -2\varnothing 2 \pm \pi - \arctan(2X) \end{aligned}$$

with X being normalized.
A next step is a description of the 4-port of Fig.3 dependant on it's components and it's input and output parameters at ports 1..4. Replacing B,b in equ. (4) by a',A' allows evaluation for a',A' of the set up of Fig.3 if a,A are known. Evaluation for b',B' is possible by replacing a,b,A,B by b,B',B,b' and

with known b,B. The same must be done for ports 3,4. Changing a..d,A..D of equ.(2) to a'..D' and then replacing a'..D' by the results of the just described evaluation yields a system of four equations for the ideal coupler of Fig.3. It's input and output parameters are expressed in terms of the input line parameters and measurable data a..D. Performing the S-parameter measurement described at the beginning of this chapter will simplify the equations because of B..D equal zero, A=1, a..d being the S-parameters of the combined set up. Finally introduction of equations (3), (6), (6a) to this equation system allows to solve for S, r, $\Phi 1$, $\Phi 2+\Psi 2$ dependant on only the measurable S-parameters of the 4-port.

Equivalence of 4-Ports and Results

Having the structured 4-port analyzed it can be shown that it describes also a general 4-port.

The preceding chapter shows, how to determine the characteristic data of the circuit of Fig.3 by measurement of scattering parameters. S determines the coupling of the ideal coupler. r, $\Phi 1$ give position and amount of the perturbation by use of equ.(7). $\Phi 2+\Psi 2$ can not be separated and indicates some internal phase length.

It turns out that there are four independant parameters determining completely a general lossless 4-port as well as the structured 4-port of Fig.3.

Expressing conversely a and b -which are S11 and S12- in terms of S, r, $\Phi 1$, $(\Phi 2+\Psi 2)$ allows to prove, that any set of S11,S12 obeying equations (2) thus can be realized. S11 and S12 are fixing also S13,S14.

Hence the hypothesis is true. Any general lossless 4-port can be represented by a combination of components like shown by Fig.3.

One main result of the analysis is that with knowledge of electrical position and value of X the perturbation can be compensated by insertion of calibrated devices like indicated in Fig.2. The other main result is that this procedure of compensating and matching the ports converts the general 4-port device into an ideal directional coupler at the same time. This is easy to understand from Fig.3. The mathematical results containing the necessary information for practical application are

$$S^2=(b^2-d^2)/(b^2-c^2)\ ; \qquad (8)$$

With $J=(1,\pm\pi/2)$;
and $p=(S(ac-bd)-Js(ab-cd))/(Sc-Jsb)$

$$r=1/|p|\ ;\ \Phi 1=\arctan(\mathrm{Im}(p)/\mathrm{Re}(p))\pm\pi \qquad (9)$$

are given. J has to be chosen for $r<=1$ before evaluation for $\Phi 1$. The amount of X and its position $\phi 1$ are readily derived from equ.(7). The sign of X may be chosen and determines $\phi 1$. For completeness $(\Phi 2+\Psi 2)$ may be also given.

$$(1,\Phi 2+\Psi 2)=(r*(1,\Phi 1)-a)/(-Srb-Jsrc) \qquad (10)$$

Practical Procedure

In the HERA rf system 500 MHz WR1800 couplers of the type of Fig.2 are used. Originally the idea was, to tune these couplers experimentally to the coupling values needed. It turned out that the coupling value itself could be modified easily by symmetrical insertion of bars or plungers to the symmetry plane. However experimentally reestablishing match and high directivity required a sequence of unmounting 4 WR 1800 flanges, carrying out mechanical changes, remount the flanges and measure for every test. As above mentioned - this procedure took too much time because of high sensitivity of match and directivity against position and impedance of induced compensations.

This was the reason to search for a theoretical solution. After finding the relations (7), (8), (9) it was possible to determine correctly an equivalent impedance X as source of perturbation by evaluation of S-parameters. Corresponding to Fig.3 it's position is defineable in the input lines.

In order to compensate it by an inductor it's sign was chosen to be negative to have a capacitor. Then the impedance of an inductive bar was calibrated moving it inside WR 1800 waveguide from electrical field zero to maximum. Now it was only one step to achieve match and high directivity : positioning 4 bars of inductivity -X at the positions of the capacitors.

Practically the calibration of the bar is valid only in an unperturbed TE10 field. Very near the coupling area of the real coupler the TE10 field is more or less distorted. Here the procedure of compensation may require more than one step.

Conclusions

A procedure was found which allows to convert any lossless 4-port into a directional coupler within one step. It was successfully applied for modification of standard WR 1800 waveguide directional couplers to different coupling values. Typical directivities of 35..40 dB and VSWR values of 1.03..1.06 were achieved at coupling values between -4..-12 dB.

Finally it has to be mentioned that much time was spent to find a purely experimental solution of the problem. Due to a given time schedule this was a reason to buy the needed couplers of the type of Fig.2 already tuned from the manufacturer. Several spare couplers were bought in order to realize in a short time any additional coupler.

References

[1] R.E.Collin Foundations for microwave engineering. McGraw-Hill, 1966,Sec.4.7,4.8