Mode Selective Directional Coupler for NLC*

S. G. Tantawi
Stanford Linear Accelerator Center, Stanford University, Stanford CA 94309

Abstract

The design method for a high power, X-band, 50 dB, circular to rectangular directional coupler is presented. The circular guide is over moded and is intended to operate in TE_{01} mode. The rectangular guide operates at the fundamental TE_{10} mode. A small percentage of higher order modes in the circular guide can cause considerable errors in the measurements because the magnitude of the axial magnetic field of these modes is higher than that of the operating mode, especially near their cutoff. We used a Hamming window pattern for the coupling slots to achieve mode selectivity. Comparison of theory and experiment will be presented.

I. INTRODUCTION

Over-moded waveguides are often used to minimize the losses in waveguide transport systems, . One key component in these systems is directional couplers. These are used either to couple power from one guide to another or to monitor the power in one guide. In either case the coupler should introduce very little mode conversion into the original guide and couples only to the design mode of operation. This paper is concerned with the design of a mode-selective directional coupler for the Next Linear Collider (NLC) RF system[1]. This system uses a circular waveguide with a 1.75" diameter. The operating frequency is 11.424 GHz. These waveguides are expected to transport RF power up to 200 MW. A directional coupler with a coupling level around -50 dB is required to monitor the power level in these guides. The guide operates in the low loss TE_{01} mode. This mode has a small magnetic field near the wall unlike other modes that can be supported by the guide. Hence, unless the coupler is highly mode selective, a small percentage of mode impurity causes errors in the measurements.

The methodology normally used in designing mode selective directional couplers for high power over-moded guides discriminates against other modes by properly choosing the distance between coupling slots [2]. As the number of modes inside the original guide is increased, the number of holes and the length of the coupler are increased. This makes the coupler hard to manufacture and very sensitive to the accuracy of slot positions and size. When this problem was studied for communication systems, it was possible to make the wavelength of the dominant mode in the side arm equal to that of the main guide. In this case, it was realized that natural mode discrimination occurs independent of slot positions [3]. However, there is no theory developed for designing couplers in a manner independent of slot position.

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In this paper we present a rigorous approach for designing mode-selective directional couplers using the analogy between the coupling between guides with slots and digital filters. The theory is presented in section II. An example of a coupler design and comparison between theory and experiment is presented in section III.

II THEORY

Figure 1 shows a schematic diagram of the problem. The circular guide is over-moded, but the rectangular guide that forms the side arm is assumed to be able to support only one propagating mode. The rectangular guide is coupled to the circular guide by the side wall (the narrow side of the rectangular guide). This means that the rectangular guide couples only with H_z (the magnetic field in the Z direction); hence the side arm will couple to no TM modes in circular guide. The coupling between a TE mode with wavelength λ_n, and an axial magnetic field $H_z{}^n$ to TE_{10} mode in the rectangular guide with wavelength λ_s can be written as a phasor addition of the contribution of each slot in the coupler; i.e.,

$$H_{z\pm}^{n,s} = \sum_{i=1}^{N} \left| H_z^n \right| C_i \; e^{-2\pi j \; z_i \; \left(\frac{1}{\lambda_n} \mp \frac{1}{\lambda_s}\right)} \quad , \tag{1}$$

where $H_{z\pm}^{n,s}$ is a phasor representing the Z magnetic field in the coupler side arm. The plus sign is for coupling in the forward direction, and the negative sign is for coupling in the reverse direction. The symbol z_i refers to the coupling slot position in the Z direction relative to some arbitrary reference. Equation (1) can be viewed as a *discrete convolution* of a signal represented by the field inside the main coupler guide as a function of z_i, i.e.,

$$s(i) = \left| H_z^n \right| \; e^{-2\pi j \; z_i \; \frac{1}{\lambda_n}} \quad , \tag{2}$$

with a filter represented by the coupling in the side arm as a function of z_i, i.e.,

$$h(i) = C_i \;\; e^{-2\pi j \; z_i \; \left(\pm \frac{1}{\lambda_s}\right)} \quad . \tag{3}$$

The output signal is then given by

$$y(l) = \sum_{i=1}^{N} s(i) \;\; h(l-i) \, . \tag{4}$$

Equation (4) is equivalent to eq.(1) at $l=0$. The input signal $s(i)$ can be viewed as a summation of different harmonics each having a *frequency* $2\pi / \lambda_s$. The filter $h(i)$ can then be designed using standard methods for Finite Impulse Response (FIR) digital filters [4]. If $N \to \infty$ and C_i is a constant, it can be seen immediately that the frequency response of the filter is $\delta(2\pi / \lambda - 2\pi / \lambda_s)$ where $\delta(.)$ is the Dirac delta function. This means that by choosing the wavelength in the side arm equal to the wavelength of the desired mode in the main guide and having long enough coupling length, the side arm will couple only to that mode. However, we do not require the coupling response to be as narrow as a delta function. It is sufficient to have a band-pass FIR filter with band width equal to $2\left|2\pi/\lambda_f - 2\pi/\lambda_p\right|$ where λ_f is the wavelength of the operating mode in the main guide and λ_p is the wavelength of the mode closest in wavelength to the propagating mode. The filter should have side lobes (or ripples) as low as the desired rejection value for the unwanted modes.

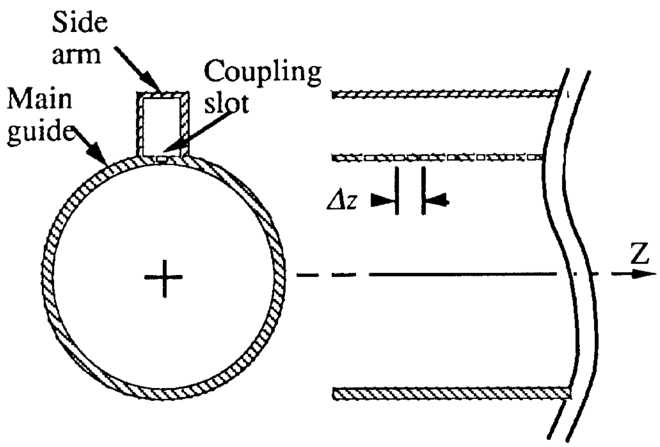


Figure 1 Schematic diagram of the basic coupler geometry

One standard and widely used FIR filter is the so called Hamming window [4]. A Hamming window with its main lobe centered at $2\pi/\lambda_s$ is given by equation (3) while substituting for the coefficients C_i as follows:

$$C_i = 0.54 + 0.46\cos\{\frac{2\pi}{N}(i - 1 - \frac{N-1}{2})\}, \quad 1 \le i \le N \tag{5}$$

Using a discrete Fourier transform one can obtain the impulse response of that filter. This is shown in Fig. 2 as a function of the normalized frequency $\theta = 2\pi\ \Delta z/\lambda$, where Δz is the separation between slots. The peak side lobe amplitude is -41 dB. The main lobe width is 8π/N. This determines the required coupler length (L):

$$N\Delta z \cong L > 2\left|\frac{\lambda_f \lambda_p}{\lambda_f - \lambda_p}\right| \tag{6}$$

The sampling distance Δz must obey the Nyquist sampling criteria, i.e.,

$$\Delta z < \lambda_{\min}/2, \tag{7}$$

where $\lambda_{\min}$ is the smallest possible wavelength in the main guide. If the slots are small and circular, the relation that governs the H_z coupling between the two guides is well known; see for example [5]. The equations that relate the propagating power to H_z, the relations relating the slot dimensions to its coupling coefficient, and equations (5) through (7) are the main design equations. The resulting mode selective directional coupler is insensitive to large dimensional tolerances between the slots.

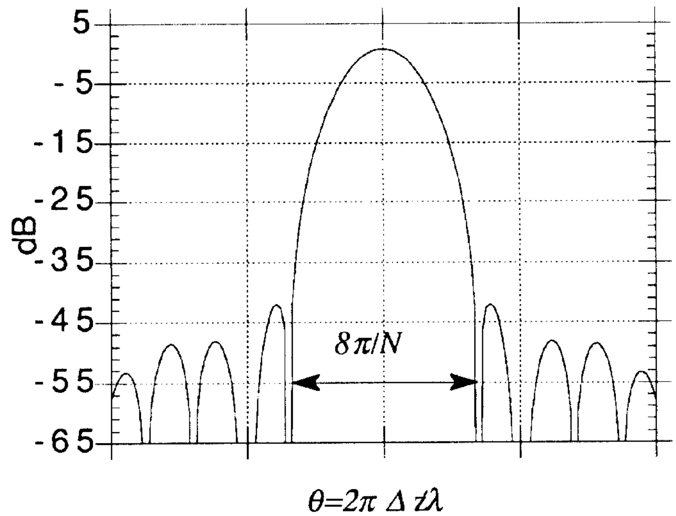


Figure 2. Hamming window impulse response

The filter impulse response, shown in Fig 2, shows a dip between each side lobe and the next. These dips will exist whether this type of filter is used or not. At the wavelengths at which a dip occurs, the distance between the slots is such that no coupling occurs. The distance between the slots can be adjusted so that the wavelength of each unwanted mode lie in exactly one of these dips. This is the normal methodology in designing couplers. However, as the number of modes gets larger, the coupler length and number of slots also becomes large. In this case it becomes very difficult to fabricate the coupler because of the tight tolerances imposed on the distances between the slots

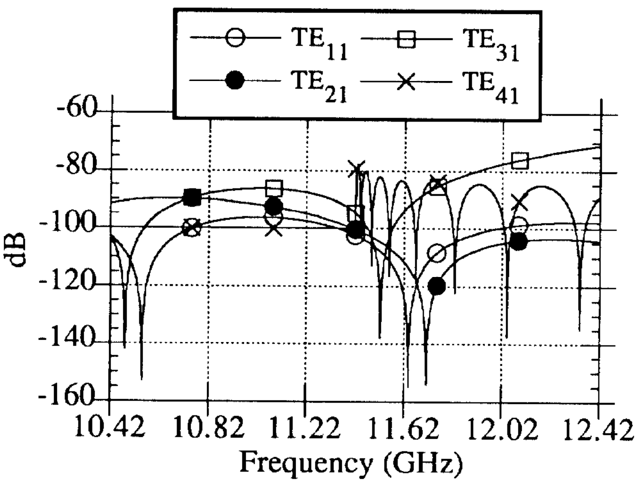
It worth noting that the filter function being used for coupling will be just as effective in eliminating any mode contamination and mismatch in the main guide due to the coupling slots. Each slot will produce an amount of mode conversion and reflection that will add up according to Equation(1). Hence, they will cancel each other according to the filter function except for the operating mode in the forward direction.

III A 50 dB COUPLER for NLCTA

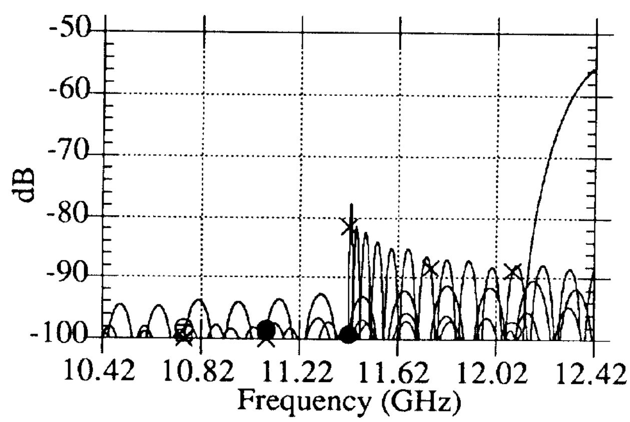
We used the design method described above to design a mode selective directional coupler for the NLCTA RF system described briefly in the introduction. The coupler has 50 holes separated from each other by Δz=0.574". This separtion agrees with eq. (7) and at the same time equals to $\lambda_f/2$ at 11.424 GHz. Thus the directivity is enhanced at this particular frequency. The coupling wall thickness is 0.03". The diameters of the holes are tailored to simulate the hamming window. The large dimension of the rectangular guide that forms the coupler side arm is 0.717". This makes the wavelength of the dominant mode in the side arm (TE_{10}) equals to that of the operating mode in the main guide (TE_{01}). To taper up from this dimension to the standard WR90

X-band waveguide, a taper was included in the bend that separate the side arm from the main guide. This bend was designed with the help of the finite element code HFSS. To keep the coupler under vacuum, the side arm was terminated by a standard SLAC vacuum window[6].

Figures 3 shows the theoretical coupling to all parasitic TE modes. Near 11.42 GHz TE_{41} has a higher coupling value relative to the other modes because it is very close to cutoff. This makes it has a very large axial magnetic field. The coupling from that mode is attenuated by more than 41 dB because of the Hamming window. If the coupler did not have a way of discriminating against that mode, a considerable error in the measurements could occur due to a small impurity in the original mode. Since the Hamming window impulse response is periodic, the coupler will start to couple well with backward TE11 after 12.1 GHz.



(a)



(b)

Figure 3. Theoretical coupling to parasitic TE modes: (a) Forward coupling (b) Backward coupling

The coupler response was measured using an HP8510 network analyzer system. We used a near perfect Marie' mode transducer to excite the TE01 mode in the circular coupler. A PC was use to control the network analyzer system and to calibrate it correctly for measurements with mixed type transducers (one for TE_{10} in rectangular guide and another for TE_{01} in circular guide). The main guide was terminated with a slowly tapered horn to simulate a matched load.

Figure 4 comparies experiment and theory for both forward and reverse coupling. The forward coupling agrees very well with theory. The reverse coupling shows a good directivity of about 30 dB. However it does not agree very well with the predicted 40 dB directivity. This can be attributed to the fact that the load which terminate the coupler has a reflection coefficient that is greater than -40 dB.

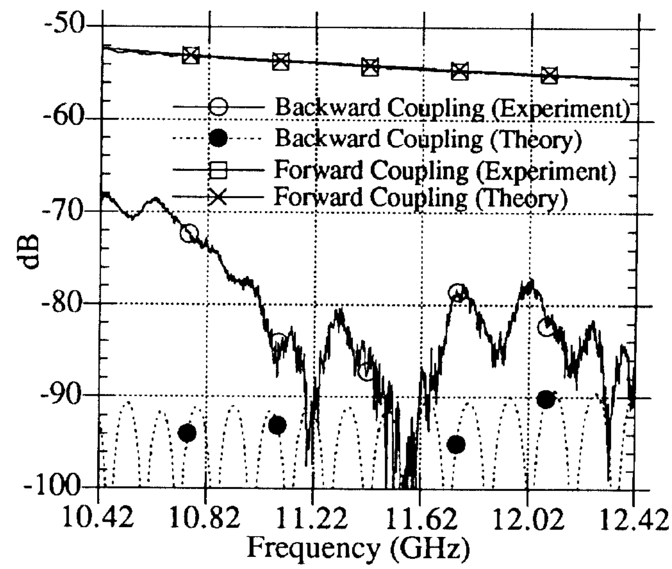


Figure 4. Comparison between theoretical and experimental coupling for the operating mode (TE_{01})

IV. ACKNOWLEDGMENT

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