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by

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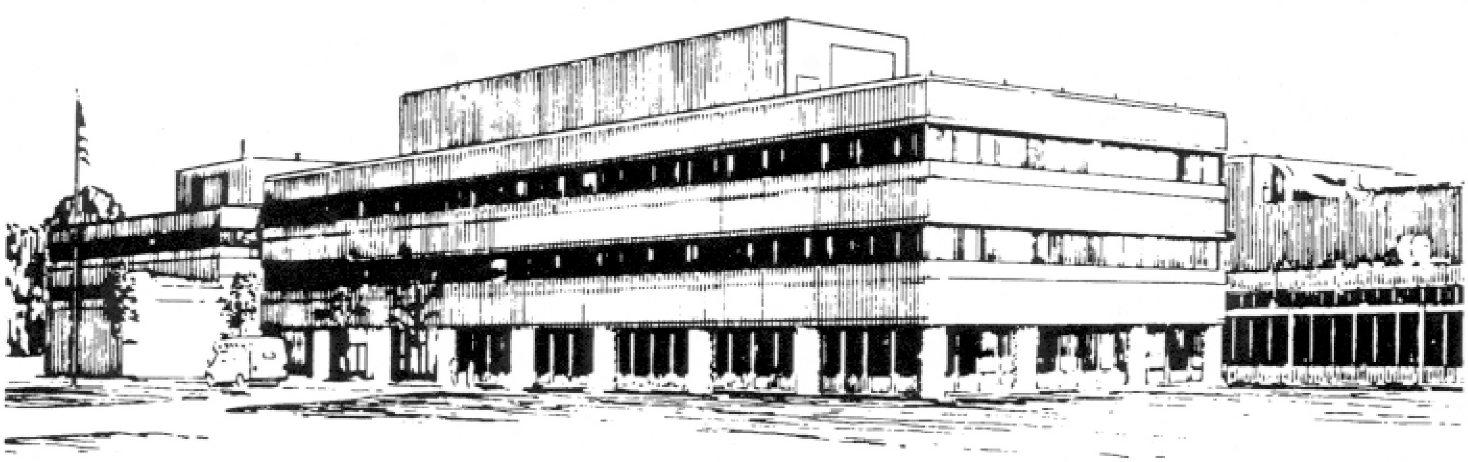

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A Third Generation Lower Hybrid Coupler*.

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Abstract-- PPPL and MIT are preparing an experiment of current profile control using Lower Hybrid waves in order to produce and sustain advanced tokamak regimes in steady state conditions in Alcator C-Mod. Unlike JET s, ToreSupra s and JT60 s couplers the C-Mod lower hybrid coupler does not employ the now conventional multijunction design, but will have similar characteristics, compactness and internal power division while retaining full control of the antenna element phasing. This is achieved by using 3 dB vertical power splitters and a stack of laminated plates with the waveguides milled in them. Construction is simplified and allows easy control and maintenance of all parts. Many precautions are taken to avoid arcing. Special care is also taken to avoid the recycling of reflected power which could affect the coupling and the launched $n_{||}$ spectrum. The results from C-Mod should allow further simplification in the designs of the coupler planned for KSTAR and ITER..

1 INTRODUCTION

A Lower Hybrid Current Drive coupler consists of an array of waveguides, phased in such a manner that the refractive index of the launched wave along the magnetic ($n_{||}$) field satisfies certain conditions (wave accessibility and damping in the desired radial location).

In early LHCD experiments, most notably in PLT, where the power coupled was modest, the coupler consisted of an array of individually fed and individually phased waveguides [1].

Most of the basic understanding of LHCD physics was established with such arrays.

As soon as LHCD started being employed as a tool to improve the plasma characteristics, more power was required to be delivered by the coupler. With the increasing number of waveguides then required the coupler feeding system became rather cumbersome and expensive. Thus, several machines (JET, Tore Supra, JT-60) [2-4] adopted a system, called the multijunction [5], in which multiple waveguides are fed by one common source. This has simplified construction and made the coupler more compact, but it suffers from the fact that the reflected power from the plasma in any given waveguide is recycled into the connected waveguides, with the potential of altering the launched spectrum uncontrollably. In addition the purity of the spectrum is limited by the built-in fixed phase difference between the group of connected waveguides.

2 THE C-MOD COUPLER

The LHCD experiment on C-Mod is supposed to deliver ~ 3 MW (4 MW source) power to the plasma through two couplers installed in equatorial ports. The first phase of the project comprises the use of 12 Klystrons and one coupler. Ultimately the two couplers will be fed by 8 Klystrons each.

The C-Mod coupler requirements presented us with the challenge of designing a coupler which provides the necessary array element phase flexibility required by a physics experiment, a large number of array elements to deliver the high power required and simultaneously a coupler which is compact enough to fit in one relatively narrow port.

The C-Mod coupler design consists of 4 vertically stacked arrays of 24 waveguides each, with each guide having the dimensions of 0.55×6.0 cm^2. The drive system employs 250 kW Klystrons and the power from each Klystron is divided into 8 waveguides, two adjacent columns of 4 waveguides each. The relative phase of the waveguides in the column is fixed (and chosen equal zero), while the relative phase between columns is controllable. This results in a fully controllable spectrum, which includes the ability to reverse the direction of the RF beam launched in the plasma.

The power splitting system and phasing control is shown in the schematic of figure 1. Each Klystron feeds two adjacent columns. The RF power is initially divided in two by a standard high power divider: the remaining division of the power in the 4 vertically stacked waveguides could be easily be obtained using a cascade of vertical 3dB dividers. For the first coupler we have chosen to use a standard power divider for the second stage of power splitting in order to gain experience especially in dumping the reflected power from the plasma. An internal 3 dB splitter is used in the final splitting of the power. The phase between the two columns is controlled by a high power phase shifter, while the phase between adjacent pairs is controlled via the low power phase shifters before the two Klystrons. It is interesting to note that with this configuration the combined use of the two kinds of phase shifters gives full control and maximum directivity of the spectrum. Also real time control of the spectrum, required for some experiments such as feedback stabilization of MHD modes, is provided by keeping the high power phase shifter fixed (which is usually slow) and varying the low power one, it is still possible to obtain a wide range of spectrum control; only the ability to reverse the RF beam and a certain degree of directivity are lost, as shown in figure 2.

Figure 3 shows an elevation view of the coupler as will be installed on C-Mod. One of the most prominent features is that the vacuum windows are brazed directly into the nose piece so that all the waveguide joints of the transmission lines are in an air pressurized environment. Arcing at waveguides junctures in vacuum has been a common source of trouble of earlier experiments and has been one of the major factors limiting the maximum power reliably coupled to the plasma. Another potential source of arcing, the existence in vacuum of the electron cyclotron layer ($\omega_o=\omega_{ce}$), is also eliminated in this design. The only waveguide run exposed to vacuum is the last ~10 cm which is copper coated for the dual purpose of not exposing Titanium to the vacuum (see later) and of decreasing the probability of multipactoring. The 3 dB power splitters are clearly visible in the figure; also at the back of the launcher, opposite from the front nose, there is a flange which can allow the insertion of a dummy load to absorb the power reflected from the plasma. In the ideal case that the reflections from the two vertically connected waveguides are in phase, there will be no power delivered to the back waveguides, and all the reflected power will then be dissipated in the dummy loads upstream in the transmission lines. But this ideal situation is expected to be highly unusual, therefore if at the end of the rejection arm there were a short, the reflected power would be recycled back into the coupler, altering the coupling characteristics and the $n_{||}$ spectrum. Because of the small width of the waveguide it is not practical to insert a dry load for long pulse operation. Thus it is highly desirable to ultimately place the dummy loads at the back end in place of a shorting plate to optimize the coupled spectrum. Our flange arrangement allows us to attach different kind of loads as we progress to higher power and longer pulse operation and most importantly allows us to inspect them for integrity.

3 CONSTRUCTION.

The front coupler channels are created by EDM process. The 24 slots in each of the four units are machined into a single block of Titanium 6242 alloy material. One mill precision for this technique is necessary to permit brazing the vacuum windows (half wavelength resonant bricks of aluminum oxide) directly into the channels without a jig [6]. The dimensions of each waveguide opening are 60 mm x 5.5 mm and the openings are separated by a 1.5 mm septum. The four coupler array units (figure 4) are bolted to a common flange and are protected from the plasma by a set of boron-nitride tiles.

Because the vacuum seal is inside the machine’s cryostat zone, it could be exposed to extremes in temperature under certain failure conditions. The requirement that the coupler vacuum seal integrity be maintained even if the coupler temperature reached liquid nitrogen temperature, imposed a severe boundary condition on the seal design.

Vacuum is maintained between the 4 couplers and the interface flange by means of a .030” diameter gold wire seal. Seal pressure for each of the couplers is provided by 28 #

10 Inconel 718 high strength bolts with an applied preload = 60% of yield. A 3/8” long stainless collar under each bolt head limits bolt stress at reduced temperatures. Since design requirements specify potential temperature extremes between +150 C to –196 C a method of heating/cooling the interface flange in the area of the gold seals has been added as a further protection against mechanical seal failure. Slots are machined in the interface flange and (4) 500 Watt 120 Volt heating elements are adhesively bonded/embedded to assure conduction and limit the lowest flange temperature to ~0°C. The heaters are trapped during assembly and a gas powered generator or un-interruptible power supply will provide the necessary back up power should an interruption in general electric power service occur. Gun drilling of the flange is used to create 2 independent coolant loops. N_2 gas or water will flow within these loops and provide the necessary cooling required to limit the maximum temperature to ~50°C. Since the coolant loop feeds are within the shroud around the coupler no coolant connections are in vacuum. All necessary instrumentation/controls will be provided to maintain/control temperatures.

The waveguide run which goes from the last standard-size component to the nose piece is fabricated by stacking 25 metal plates, 24 of which have the waveguide pattern milled in them (see figure 5). The whole assembly is then bolted together: in this manner a very simple and inexpensive machining process creates the channels required for the whole transmission line. In addition, any maintenance can be done with relative ease. The stack of plates is divided in two sections: the section which feeds directly into the nose piece is made of 300 series stainless steel, with the waveguide channel copper coated, in order to reduce the electromagnetic forces. This section also incorporates a H-taper which transforms the long dimension of the waveguide from the standard WR187 to a larger dimension, 60 mm, to decrease the power density on the window.

The second section is fabricated in aluminum and houses the 3 dB divider. At the input of the plate assembly there is a E-taper section which transforms the narrow dimension of the waveguide from the standard WR187 to the desired width of 5.5 mm. At the juncture of the two sections the array of 96 waveguides in the aluminum section meet the 96 waveguides of the stainless steel section. In order to avoid gaps which could cause arcing, we will insert a approximate .010” thick copper gasket fabricated by the EDM process.

As mentioned earlier, it is desired to have the same phase in the 4 waveguides in a column. Not only is the physical length of the waveguides different because of the poloidal curvature, but the 3 dB divider introduces a 90° delay in the secondary waveguide. Normally the phase could be balanced with a fixed phase shifter, but we can take advantage of the different waveguide wavelength before and after the H-taper: by appropriately staggering the tapers, a phase compensation can be achieved without introducing a separate phase shifter section.

Surrounding the stainless steel stacked plates that mate with the nose piece is a 300 series stainless steel shroud. The shroud provides an extension of the vacuum boundary out to a position where an adapter box and a welded bellows assembly are incorporated. The shroud consists of two “U” shaped halves, welded along the horizontal seam and around the perimeter at each end to an interface flange at the coupler end and to a support flange at the other end. Vacuum surrounds the exterior of the shroud and atmospheric pressure is internal in the area of the stacked plates. This unique design, which eliminates these waveguide joints in vacuum reduces the arcing concerns found in earlier designs. In addition to providing a vacuum extension/boundary the shroud provides a means to transfer loads from the waveguide and coupler into the machine port extension via supports. The adapter box and bellows assembly mate to the Alcator C-Mod port extension at one end and to the previously mentioned waveguide support flange at the other. The bellows allows a radial motion of the assembly of 20 cm. This radial positioning capability provides coupling optimization and permits the coupler to be retracted during machine conditioning. It also allows compensation for small angular misalignments during installation into the port.

4 DIAGNOSTICS

In order to better understand the flow of reflected power in the coupler, two sets of probes are used to monitor the reflected power in the top and bottom waveguide in each coupler column of 4 waveguides. By monitoring the power in the upper (or lower) waveguide and the power in the rejection arm it is possible to reconstruct the reflection pattern on the whole coupler.

This compact probe consists of 2 current loops, a directional coupler, and a small trimmer capacitor (figure 6). These two current loops are placed on the narrow side of the reduced waveguide with a quarter guide wavelength ($\lambda_g/4$) spacing corresponding to 22.4 cm. Since the current loop is sampling a small portion of the H_z field in the TE_{10} mode, the loop coupling value is determined by the intercepting area perpendicular to the H_z field. In fact, the current loop can be treated as a small loop antenna with very low impedance. Because of the low coupling value from the waveguide, such as –40 dB or less, this low impedance value is desired. Even though this might cause some mismatch to the rest of the system, the directional coupler functions as a buffer and alleviates this mismatch problem.

Due to the directional coupler characteristic, the coupling port will introduce 0^o phase shift and the direct port will introduce 90^o phase shift. When these two current loops are connected to the coupling port and direct port of the coupler respectively, the phase difference will be either 0^o or 180^o depending on the propagation direction of the wave in the waveguide at one of the port of the directional coupler as illustrated in Fig. 6(a) and (b). In order to match the coupling value of the directional coupler, the coupling value of the current loop connected to the direct port has to be reduced accordingly by decreasing the intercepting area. This can be achieved through turning and/or pulling out the current loop. Since a small machining error is inevitable, a trimmer capacitor is attached to one of the current loop in order to compensate the phase error.

Incidentally these same probes will be used for the phase calibration of the whole coupler and for any phase check, by shifting the detector to the other output so that forward power is then monitored.

5 CONCLUSIONS.

The coupler for the LHCD experiment on C-Mod has been designed not only to conform to the constrained environment of the machine, but also to optimize the ability of LH waves to drive current in the plasma. The result is a very compact and streamlined design which has the maximum flexibility in terms of launched spectrum.

The main characteristics are:

- full control of the phase, including the ability to reverse the direction of the RF beam. This control, without being able to reverse the current, is possible in real time for feedback stabilization experiments.
- minimization of arcing by having no waveguide joint in vacuum, having the $\omega_o=\omega_{ce}$ layer in the pressurized section of the transmission line and by adding multiple channel copper gaskets at each junction of the array.
- inclusion of dummy loads, easily serviceable, prevents the spoiling of the launched spectrum by the recycling reflected power.
- fabrication is simplified, as is the installation and the maintenance
- diagnostic probes will provide essential information for an even simpler design for the second coupler and for the advanced coupler foreseen for KSTAR.

6 AKNOLEDGMENTS

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7 FIGURE CAPTIONS.

Figure 1 Each Klystron feeds two adjacent columns of waveguides.

A high power and a low power phase shifter allow full control of the spectrum.

Figure 2 $n_{\|}$ spectrum for various progressive phase differences between adjacent waveguides (line), compared to the spectra obtained by keeping the high power phase shifter at $\Delta\Phi=90°$ while changing the phase in the low power phase shifter (gray)

Figure 3 Elevation view of the coupler.

Figure 4 Front and rear view of the front piece.

Figure 5 Construction of the transmission line with stacked plates.

Figure 6 In (a) the forward power at the power detector is out of phase: no power will be detected. The in-phase power will be absorbed by the 50Ω dummy load.

In (b) the reflected power at the 50Ω dummy load is out of phase. No power will be absorbed. The in-phase power will appear at the power detector.

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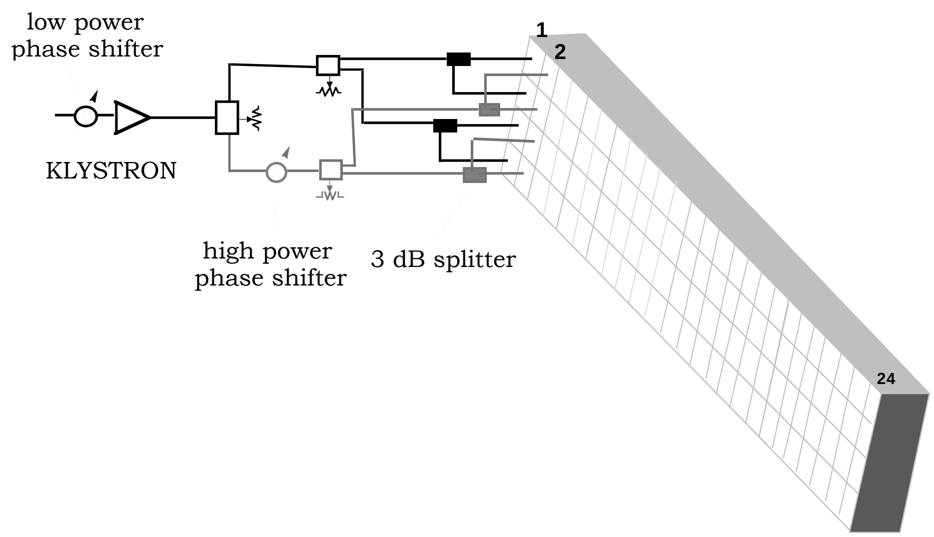

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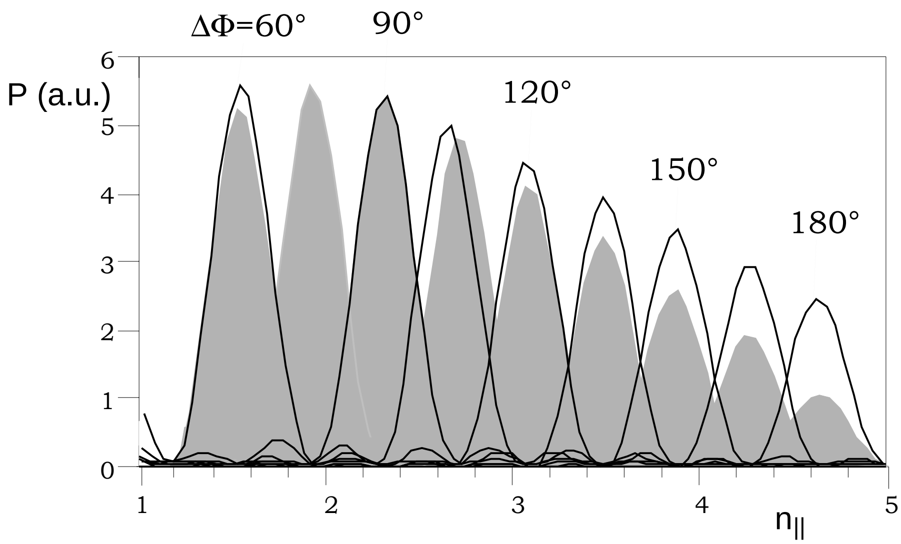

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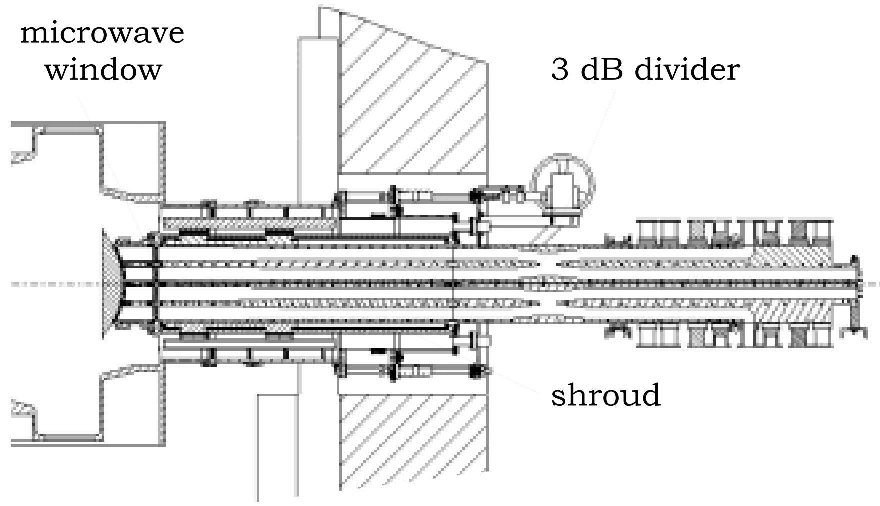

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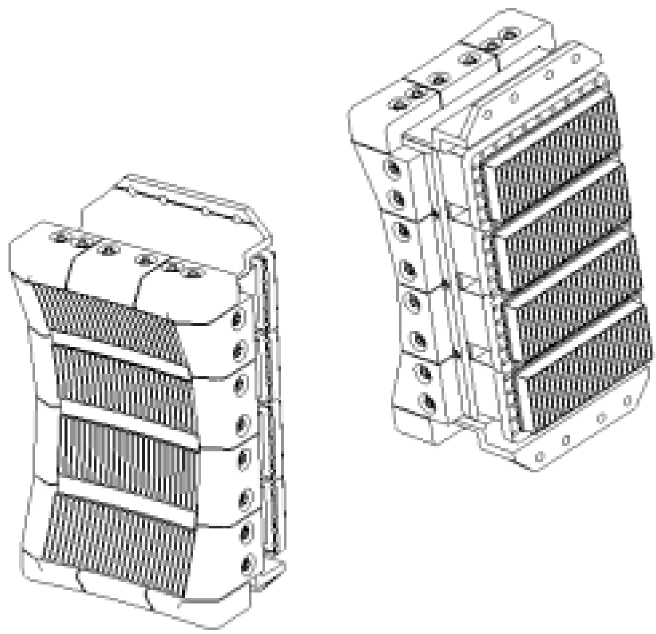

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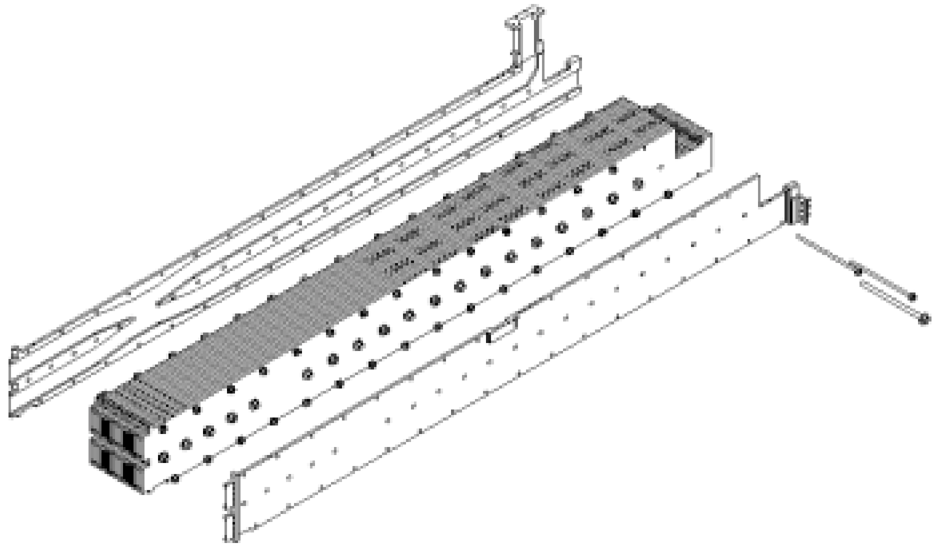
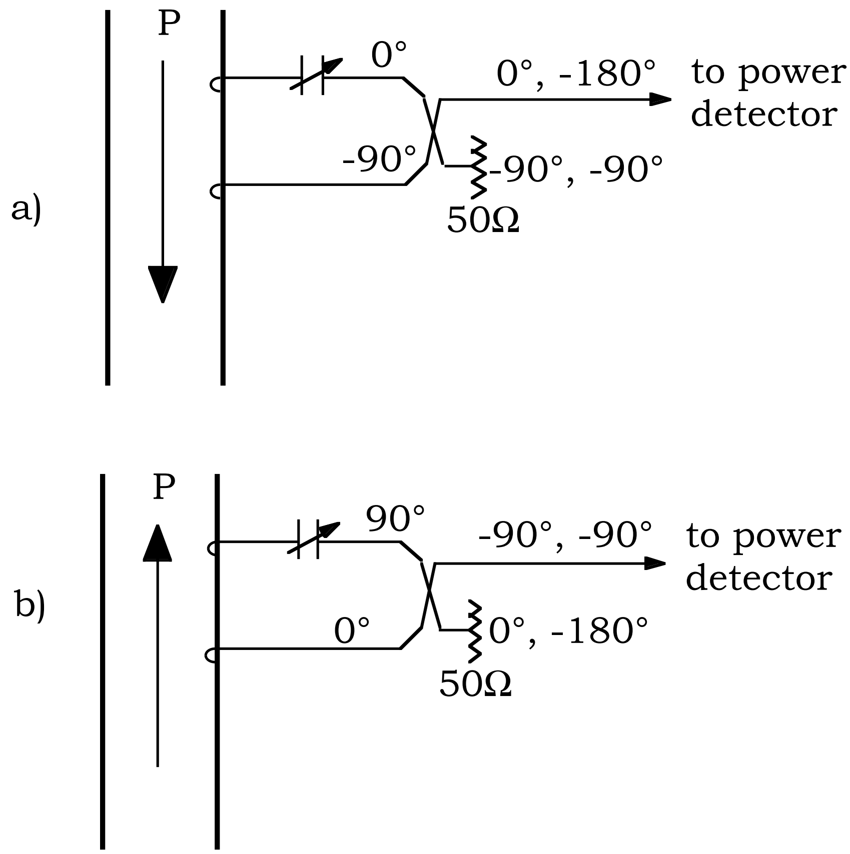


Figure 5 Construction of the transmission line with stacked plates.



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