High Performance Dual Directional Couplers for Near-mm Wavelengths

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***Abstract*—A low loss, high directivity dual directional coupler has been developed suitable for fabrication in waveguide bands up to WR3 (220–325 GHz). The design uses waveguide split on the E plane centerline with three waveguides running side by side and coupling holes made by drilling through all three guides. Construction is relatively simple and the resulting structure is very robust mechanically. Typical coupling is 15 dB, directivity is 25–30 dB, and the insertion loss of the WR3 coupler is 0.5 dB.**

***Index Terms*—Directional couplers, machining, millimeter wave directional couplers, waveguide couplers.**

I. INTRODUCTION

WAVEGUIDE directional couplers are a critical part of microwave test equipment, and are well developed as components at frequencies up through WR10, with relatively high directivity. Couplers are normally manufactured according to a conventional design using many weak coupling holes, with diameters varying along the length to achieve optimal directivity. At low frequencies this leads to very high directivity because manufacturing tolerances are very good relative to the accuracy required, and the long length does not cause excessive loss. At higher frequencies the conventional method of construction leads to parts which are much longer than needed for the coupling alone, and can not be justified by the directivity which is achieved. Most mm-wave couplers are made with waveguide sections joined in the H plane, either with the two waveguides milled in solid blocks with coupling holes cut in a thin metal sheet separating them, or using modified extruded waveguides in which holes are cut in the broad wall of one waveguide and a second waveguide then soldered to the top. Poor directivity occurs because holes vary from the correct diameters, and because of poor joints between the parts which degrade the match and greatly increase the loss. Typical commercial couplers in WR10 have a loss of 1.5–2.5 dB, although couplers with a loss of 0.5 dB have been made [1]. In WR5 the typical loss is ~ 2.5 dB near 200 GHz. Directivity can exceed 35 dB in WR10 but deteriorates to < 20 dB at 200 GHz.

As components become feasible at ever higher frequencies, there is a need for a coupler design which has lower loss and moderately high directivity, and which is optimized for manufacturing. Low loss is particularly important in the study of submillimeter frequency multipliers, whose input match is power sensitive, and where the available input power is rarely more than required for proper operation.

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II. COUPLER DESIGN

Waveguide split along the E plane centerline is preferred for mm-wave components, because it can be easily machined with a joint that does not cause significant loss. It has proven feasible to make many components this way in two-piece split blocks, with no additional inserts. The goal of this design was to use this style of construction for a dual directional coupler, optimized for CNC machining.

For simplicity round coupling holes are used, all of the same diameter. This ensures that even if the hole size differs from the intended size, the directivity will not suffer, although the coupling will change. The behavior of the coupling of these holes was studied using HFSS [2]. With round holes, flattest coupling across a standard waveguide band is achieved by offsetting the holes by $0.285a$ (where a is the waveguide width) from the waveguide center line. Higher coupling is achieved by using two rows of holes, on either side of the centerline. High directivity is achieved by spacing holes by $0.38a \cong \lambda_g/4$, using an even number of holes in each row, and using as many holes as possible. Offsetting the rows to produce an unpaired hole at each end of the row improves the directivity over the full band, by tapering the coupling. It was found that two rows of eight coupling holes, offset by one hole, would produce a directivity of > 30 dB across a full waveguide band. With a hole size small enough to prevent excessive weakening of the wall ($\phi = 0.30a$), a coupling of 15 dB can be achieved. This coupling is about optimal for many low power applications, because it provides a strong coupled signal with only a 0.14 dB decrease in the transmission. Higher coupling at somewhat higher directivity can be achieved by adding pairs of holes to both rows (13 dB for 10 hole pairs).

With two waveguides in a single block, drilling through the dividing wall requires drilling through at least one of the outside walls. These access holes cause almost no change in performance and do not need to be filled, if the outer wall is thick enough to completely cut-off any leakage. A dual coupler can be made by running three waveguides side by side and drilling the same holes through both dividing walls (and the outer wall of one). Surprisingly, this dual coupler is no different in performance relative to two independent couplers along the same waveguide, except that there is a weak coupling between opposite side arms. Thus manufacturing a dual coupler becomes nearly as easy as making a single coupler. The total length of the coupling section is $3.7a$, so that for any mm-wave band, the length is dominated by the size of flanges and other mechanical considerations. The coupler geometry is shown in Fig. 1.

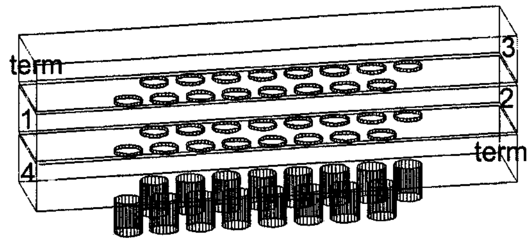

Fig. 1. Solid model wireframe drawing of the dual coupler. The main waveguide is in the middle, with the two coupled waveguides to either side. The access drilled holes are shown at the bottom. The outside surface of the block, and the bends in the coupled arms, are not shown for simplicity. Waveguide dimensions are in the standard 2:1 ratio.

The asymmetry in construction due to the access holes leads to 0.3 dB larger coupling for S_{31} than for S_{42}.

The coupling holes must be in a very thin wall (75 μm thick at 100 GHz) in order to maintain good coupling, otherwise they begin to show a significant loss of coupling and a frequency slope. It is not possible to drill holes through these thin walls unless they are fully supported, and this is not practical in this style of construction. Instead, the technique used is to drill the holes through solid metal before the waveguides are machined. Then the center waveguide is machined (with a conventional end mill) and filled with an easily applied and removed material such as hard wax. The adjacent waveguides are then milled while the wax supports the walls. It should be noted that with very high spindle speed (70000 rpm) the walls may be milled down to final thickness without any support. Drilling the holes from the outside of the block is possible only by thinning the outside wall to the minimum thickness in this region, by milling an access cutout (present on only one side). This cutout prevents making the couplers as short as would otherwise be possible. The terminated ends of the coupled waveguides are also brought out to the flange face so that loads may be placed in them while measuring the VSWR of the coupled port. The layout of a WR3 coupler is shown in Fig. 2. By machining in aluminum (alloy 6061), no plating is required.

The minimum length for the coupler is just the size of the flanges on the coupled ports, or 0.75 in (1.90 cm), and this is what is used for WR3. At lower frequencies, a slightly longer length, up to 3 cm in WR10, is needed because of the increased coupling length. For comparison, typical commercial couplers are 10 cm long.

III. Test Results

The measured performance is very close to the HFSS predictions. Fig. 3 shows the forward coupling (S_{31}) and directivity (S_{41}/S_{31}) of a WR10 model with 10 pairs of holes. The coupling is flat to within ± 0.5 dB over the 75–110 GHz band, and differs between the two arms by 0.5 dB. The directivity exceeds 30 dB over nearly the full band, including the termination, but decreases to 27 dB at the worst point. Design coupling is 13 dB in midband, but the wall thickness is about 10 μm less than designed resulting in 0.6 dB higher coupling. The variation across the band is as predicted. The predicted directivity is > 31 dB across the waveguide band, but numerical noise in the HFSS solution prevents more detailed predictions.

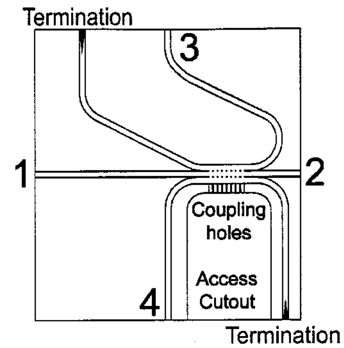

Fig. 2. Layout of the ports of a dual coupler for WR3. The asymmetry in the path lengths 1–3 relative to 2–4, leads to a difference in coupled power relative to predictions. The ports marked *Termination* are internally terminated.

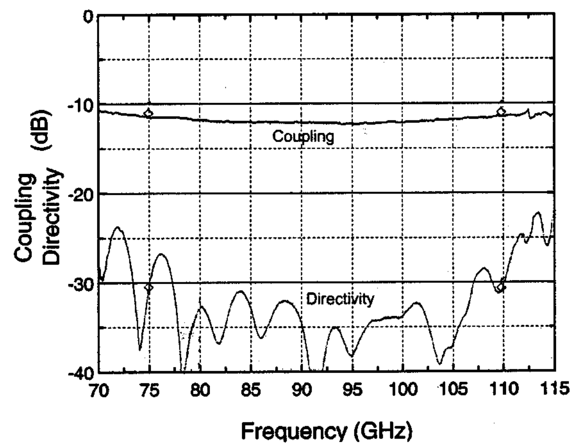

Fig. 3. Measured coupling and directivity of a WR10 coupler using ten pairs of holes, machined in E-plane split block. The markers show the band limits.

The ripple in the directivity is probably due to the coupled arm termination combined with the coupling itself, and suggests that the coupler itself is better than 30 dB. A WR6 coupler shows essentially the same behavior although it was not possible to sweep the entire band. For couplers machined from aluminum, and left unfinished, the loss is 0.15 dB at 100 GHz and 0.4 dB at 140 GHz (not including coupled power).

A single WR3 coupler has been carefully tested, out of several that have been made. Measurements were made from 220–320 GHz using a swept source consisting of an active doubler and passive tripler to WR10 band, followed by a medium power amplifier [3], and finally a wide band planar tripler [4]. The output power of this chain was 0.5–3 mW. Using a scalar analyzer [5] and commercial detector [6] the full band coupling and directivity were measured and are shown in Fig. 4. The detector linearity was not known, so the coupling and insertion loss were measured with a well matched power meter averaged from 252–263 GHz (swept to eliminate ripple). At this frequency the insertion loss is 0.5 dB, forward coupling S_{31} is 16.1 dB and reverse coupling S_{42} is 15.7 dB, consistent with the detector measurement. This coupling (corrected for loss) is 0.5 dB greater than predicted, and it is difficult to make sufficiently accurate dimensional measurements on the blocks to confirm the accuracy of predictions. The swept noise floor is high enough at most frequencies to prevent measuring

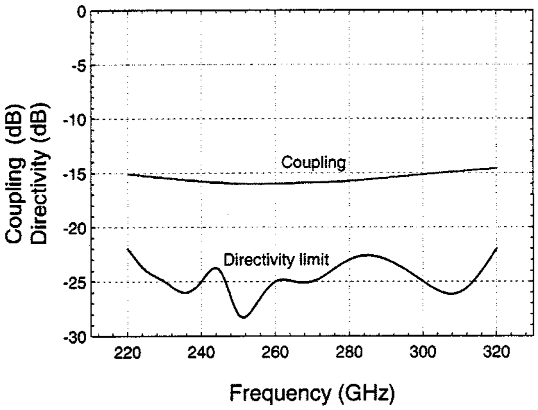

Fig. 4. Forward coupling, S_{31} and directivity for WR3 coupler. The directivity is just a limit due to the measurement noise, except from 240–270 GHz. Reverse coupling is 0.4 dB higher.

the expected directivity, but does show that the minimum directivity exceeds 22 dB across the band. Between 240 and 270 GHz the power was high enough to actually measure the directivity, which was 24–28 dB. The predicted directivity is > 30 dB across the band measured. In this band it is very difficult to measure better performance due to a lack of well characterized loads, and flange quality is also critical. The best load available was a slowly tapered rectangular feed horn. The directivity is dependent on the internal loads and some difference in performance could be seen with changes in these loads. This reflectometer has been used to measure the output match of a 280 GHz doubler, and the input match of an 800 GHz tripler, and has yielded good results.

At present waveguide bands are not well defined above WR3, but the technique used is feasible to at least 500 GHz if the walls between the coupled waveguides are thickened somewhat relative to the present design. The general method of machining is otherwise not a problem. Probably the principle difficulty is the lack of sufficiently precise flange standards.

IV. Conclusion

A directional coupler using a new type of construction offers excellent performance in millimeter to sub-mm waveguide bands, with 25–30 dB directivity and very low insertion loss. The method of construction is well suited for CNC machining at moderate cost. The couplers are extremely small, and mechanically robust. WR10 through WR3 models work very well and it appears that even higher frequency bands are feasible. These couplers enable the construction of scalar reflectometers and even vector network analyzers in bands where it was previously impossible. The small size makes them ideally suited for wafer probe stations, and other compact instrumentation.

Acknowledgment

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