A Wideband Variable Waveguide Coupler for Millimeter Applications

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***Abstract*— We present a variable waveguide coupler for the short millimeter-wavelength range. The coupler has low ohmic and insertion losses in all paths, flat coupling characteristic, and high directivity over a large bandwidth. The construction of the coupler allows a variable independent adjustment of power transferred into several paths when several couplers are used in series. The coupler is therefore useful for multichannel receivers and especially for superconductor–insulator–superconductor (SIS) mixer arrays where individual local oscillator (LO) power adjustment might be necessary. We present measurements for a coupler working at 230 GHz and compare them with a simple analytical model.**

***Index Terms*—Variable waveguide coupler, millimeter waves.**

I. Introduction

LOW-LOSS coupling in the millimeter- and submillimeter-wavelength region is not an easy task. Quasioptical methods are often employed offering a wide range of possibilities by interferometric or simple beamsplitting means. A drawback of these methods is the large size of typical quasioptical setups and the low isolation of the different paths. Waveguide couplers are compact and widely used up to frequencies of 350 GHz while offering very good performance. High directivity wideband couplers, however, require a very high-precision machining in order to obtain a specific coupling. Variable waveguide couplers overcome this problem.

Here we describe a wideband variable waveguide coupler at frequencies from 205 to 275 GHz which is also suitable for cryogenic operation. The variation can be obtained by a linear actuation with very little force requirement and a travel of 0.54 mm. The coupler allows a variation between 14 and 24 dB with a directivity of better than 15 db. The power transmitted through the main path is varied by less than 0.5 dB while varying the coupling by 10 dB. The coupler is therefore interesting for multichannel instruments where, for example, local oscillator (LO) power has to be used in an optimal serial way while allowing adjustment of the coupled power individually for each receiver channel.

II. Working Principle

The coupler is based on the principle of a multihole sidewall coupler and the mechanical outline for a fixed coupling version which was designed by M. Carter [1] for the millimeter range. The coupling between waveguides by an equidistant series of $N+1$ holes is given by

$$\frac{C}{[dB]} = -20 \cdot \log \left| \sum_{n=0}^{N} C_n exp(-id(n\beta_1 + (N-n)\beta_2)) \right|. \quad (1)$$

The directivity can be calculated to be

$$\frac{D}{[dB]} = -20 \cdot \log \left| \sum_{n=0}^{N} D_n exp(-ind(\beta_1 + \beta_2)) \right| - C. \quad (2)$$

C_n and D_n are the forward and backward coupling coefficients for the individual holes, d designates the distance between neighboring hole centers, and $\beta_{1,2} = 2\pi/\lambda_{g1,g2}$ are the phase constants for the guided wavelengths $\lambda_{g1,g2}$ in the two waveguides. For most applications $d \sim \lambda_g/4$ is chosen for a center frequency of the coupler in order to obtain a maximum directivity. For circular mid-sidewall holes of diameters d_n between rectangular wave guides with dimensions a and b, we have [2]

$$C_n = D_n = iA_n \cdot \frac{\pi\sqrt{\lambda_{g1}\lambda_{g2}}}{12a^3b} \cdot d_n^3. \quad (3)$$

Here A_n designates a correction factor for the nth hole, taking the finite wall thickness t between the guides into account. Treating the holes as circular waveguides beyond the cutoff frequency one derives [3]

$$A_n = \exp\left(\frac{-2\pi t}{1.706 \cdot d_n} \sqrt{1 - \left(\frac{1.706 \cdot d_n}{\lambda}\right)^2} \right) \quad (4)$$

where $\lambda = c/f$ is the free-space wavelength.

The coupling can now be widely changed by continuously changing the propagation constant in one of the guides. In this case the forward coupling is decreased by phase differences between the waves coupled through the individual holes. The same effect also will decrease the directivity, as the backward-coupled waves do not cancel completely. This analysis does assume that the field distribution in the waveguides is essentially the same for different propagation constants.

We propose to insert a dielectric vane along the coupling section in the E-plane of one of the waveguides in order to reduce the phase velocity in this guide (Fig. 1). Variable insertion depth will result in variable propagation constants along the coupling holes. The dielectric vane section can also be considered as a variable phaseshifter along the path of the coupler. The advantage of such a geometry is that the slit in

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the midplane of the waveguide does not greatly influence the properties of the guide as long as it stays narrow in respect with a. The movement of the vane is linear and does not require any mechanical force, an important point for cryogenic applications. As in phase shifters or attenuators of similar geometries, a taper of the dielectric vane at both ends can be used to improve the match.

The guided wavelength for the fundamental mode in the unperturbed guide is $\lambda_g = \lambda/\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}$. The change in phase velocity by a completely inserted vane can be evaluated for the fundamental waveguide mode by the resonance condition between the part of the wave propagating in the dielectric vane with dielectric constant ϵ and the part propagating in free space [4]

$$\sqrt{\frac{\epsilon-\left(\frac{\lambda}{\lambda_g}\right)^2}{1-\left(\frac{\lambda}{\lambda_g}\right)^2}}\cdot\tan\left(\frac{2\pi\sqrt{1-\left(\frac{\lambda}{\lambda_g}\right)^2}}{\lambda}\right)\cdot\frac{a-dv}{2} = \cot\left(\frac{2\pi\sqrt{\epsilon-\left(\frac{\lambda}{\lambda_g}\right)^2}}{\lambda}\right)\cdot\frac{dv}{2} \tag{5}$$

a transcendental equation which can be solved numerically for λ_g. With (5) we can calculate the maximal ratio of the propagation constants in the two waveguides of the coupler $\gamma = \beta_1/\beta_2$ for different dielectric constants ϵ and vane thicknesses dv for a given waveguide geometry. It is important to notice that γ does decrease with increasing frequency. This compensates for part of the coupling slope which is due to increasing geometrical phase delay along the coupler and therefore makes the coupling characteristics relatively flat.

III. Construction of a 230-GHz Coupler

To experimentally verify the proposed principle of a variable directional coupler we chose a basic design of a 13-hole Chebyshev coupler for a center frequency of 230 GHz (WR4, 1.09 × 0.545 mm, see Fig. 1). The second path of the coupler is doubly curved to allow a geometrical separation of all ports. The distance t between the guides is 50 μm and $d_{0,11} = 294$ μm, $d_{1,10} = 325$ μm, $d_{2-9} = 380$ μm with a distance of 400 μm between holes. The nominal coupling of such a geometry (without dielectric insert) is about 14–16 dB, a value which is well suited for typical applications like low-noise mixers. The number of holes, and therefore the length of the coupling section, is not only determined by the required coupling, flatness, and bandwidth of the coupler, but also reflects mechanical limitations like remaining material between neighboring holes and general machining precision. The coupler in its present geometry has optimum directivity for lowest coupling, a figure which could be changed by choosing slightly larger distances between the holes. In this case the mean directivity for different couplings could be further optimized.

The coupler consists of three mechanical units where the two waveguides are split along the E-plane. Such a design allows conventional high-precision machining of the waveguide halves and the coupling holes with minimized losses due to the splitting of the waveguides. The coupler is fabricated in brass for reasons of machining precision. Further gold plating is possible but has not been employed although this would reduce waveguide losses significantly, especially under cryogenic conditions. A variation of γ between 1 and 1.35 allows variation of the coupling by about 10 dB without a decrease of the directivity much below 20 dB. Larger γ's would result in larger coupling variations but also drastically reduce the directivity of the coupler. As a compromise between vane thickness (demanding at least an equivalent slot in the waveguide), mechanical stability, and machinability of the material, we used a 150-μm-thick Rexolite vane ($\epsilon = 2.5$). We chose a simple tangential radial taper with a radius of 11 mm resulting in tapering sections with a length of about $2\lambda_g$.

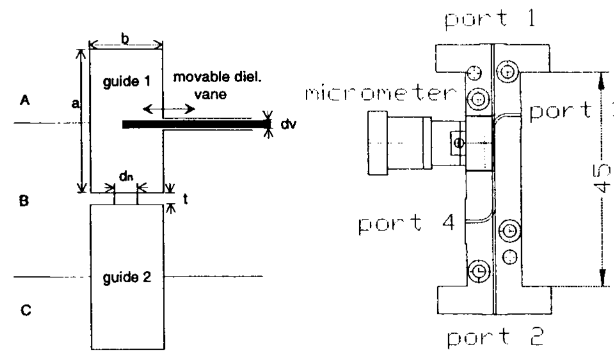

Fig. 1. Construction of the coupler. A, B, and C designate the three mechanical parts which are machined separately.

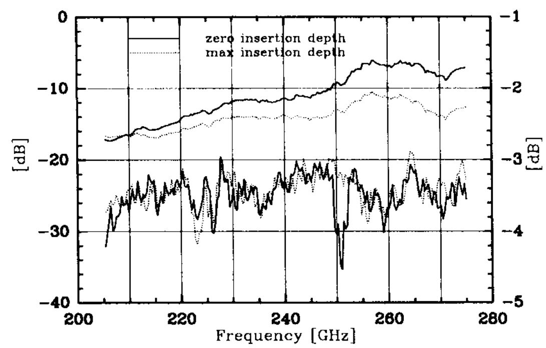

Fig. 2. Lower traces, left-hand scale: input return loss of the coupler for the extreme positions of the dielectric vane. Upper traces, right-hand scale: transmission through the coupler for extreme positions of the vane.

IV. Measurements

We used a HP 8510 network analyzer with a high-frequency extension [5] to measure the function and characteristics of the machined coupler. The return loss is shown in Fig. 2 (lower traces) and is better than −20 dB for all insertion depths; this shows that the taper of the insert is sufficient. The loss in transferred power is given in Fig. 2 (upper traces). About 2 dB are due to ohmic losses in the waveguide. Experience shows that gold plating would reduce this value to 0.7 dB at room temperature. The transferred power changes by less than 0.5 dB between maximal and minimal coupling, a value

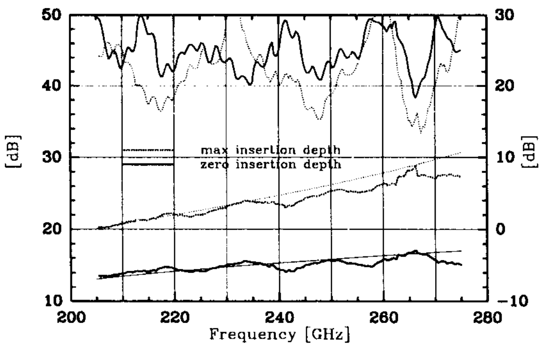

Fig. 3. Lower traces, left-hand scale: maximal and minimal coupling with dielectric vane completely inserted and completely removed. Thin lines reflect the result of the simple analytical model. Upper traces, right-hand scale: derived directivity for extreme vane positions.

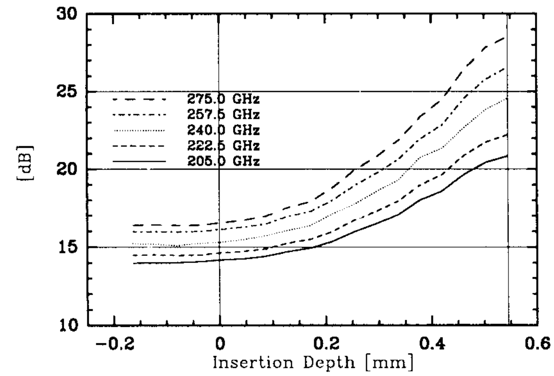

Fig. 4. Coupling variation with insertion depth of the dielectric vane. The two vertical lines show the geometrical limits of the waveguide.

low enough to allow nearly independent adjustment of several channels in a series of identical variable couplers. The fact that the loss increases with increasing insertion depth and comparison of results from a scaled model at 10 GHz with model calculations indicate that most of this change is due to losses in the dielectric material and leakage of power through the insertion slot. This slot had to be larger than the dielectric insert for reasons of mechanical precision. The general performance of the coupler could be further improved by gold plating of the guides, a dielectric material with lower high-frequency losses, and higher precision for the waveguide slot.

Fig. 3 (lower traces) shows the forward coupling without the dielectric insert and complete insertion of the vane in comparison with the calculations. The general agreement is good. Fig. 4 shows the variation of the coupling with varying insertion depths of the dielectric vane. The variation is 7.5 dB at 205 GHz and 12 dB at 275 GHz. The variation is a monotonic function of the insertion depth, an important point for practical applications.

The directivity for the two extreme vane positions (Fig. 3 upper traces) was derived from coupling and isolation measurements. The derived directivity stays better than 15 dB between 205 and 275 GHz. Measuring the isolation is highly demanding on the dynamic range of the measurement system and we suspect that the dips in directivity partially reflect insufficient dynamic range of the measurement setup or an imperfect termination of port 2.

V. Conclusions

We have proposed and experimentally verified a novel variable waveguide directional coupler for the millimeter range. The principle has been successfully applied up to 275 GHz. The coupler allows for serial distribution of LO power in multichannel systems with individual independent adjustment of the power coupled to different paths. The mechanical outline allows for cryogenic applications with low force, small travel actuation.

References

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