Substrate-Integrated Waveguide-to-Microstrip Couplers for Integrated-Circuit Antenna Applications

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Abstract— **In order to implement automatic gain control arrangements in receiver applications, multi-aperture couplers between microstrip circuitry and substrate-integrated waveguides are proposed. The design procedure is described, and couplers formed by single-aperture and dual-aperture configurations are presented. It is demonstrated that the coupling can be as tight as 1 dB but that weaker coupling leads to more broadband and flatter coupler performance. Designs are carried out in an HFSS environment; comparisons with CST validate the design procedure. Dimensions and parameters of all couplers are presented as guidelines for general design purpose**.

I. Introduction

Substrate-Integrated Waveguide (SIW) circuitry is in the process of maturing into a reliable and reproducible technology. Its equivalency with waveguide-based design guidelines is well documented, e.g. [1], [2], and applications are running from around 30 GHz [3], to around 100 GHz [4], [5].

Following the development of Antipodal Linearly Tapered Slot Antenna (ALTSA) arrays in SIW technology [6] for receiver applications, coupler arrangements to implement automatic gain control are in demand. As the gain control circuit will normally employ coaxial-type (TEM-like) transmission lines, a direct SIW-to-microstrip coupler would appear to be the design of first choice. A drawing of such a coupler including the receiving ALTSA is shown in Fig. 1.

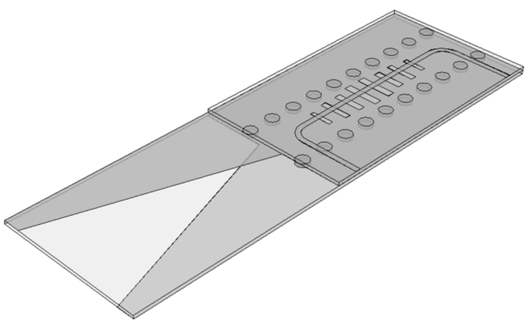
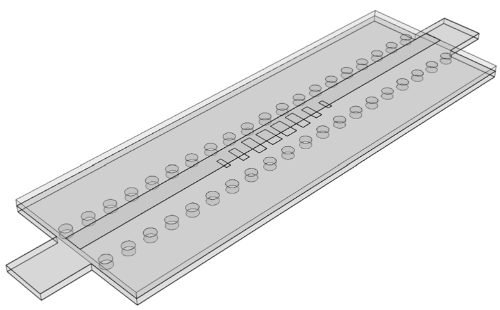


Fig. 1. Antipodal linearly tapered slot antenna with substrate-integrated waveguide connection and multi-aperture coupler to microstrip technology.

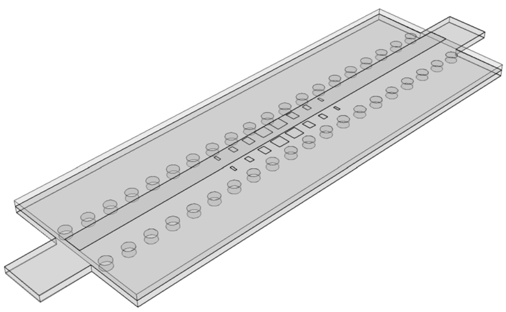
Therefore, this paper investigates SIW-to-microstrip couplers for SIW receiver applications. Performances of couplers with multiple apertures in single- and dual-slot arrangements are presented covering coupling values between 1 dB and 10 dB.

II. Coupler Design

Fig. 2 shows the arrangements of a microstrip line coupled to a SIW through single-slot (Fig. 2a) or dual-slot (Fig. 2b) rectangular apertures. Note that the curved microstrip lines in Fig. 1 have been omitted for computational efficiency in the initial design procedure. The design is performed in HFSS, and all-dielectric waveguide ports are used as SIW transitions (instead of microstrip tapers) in order to increase accuracy and dynamic range and to decrease computational complexity [2].



(a)



(b)

Fig. 2. Microstrip-to-SIW coupler with 8 single (a) and double (b) apertures.

Fig. 3 shows the individual design parameters for the SIW-to-microstrip coupler. For a given frequency range (Ka-band) and SIW substrate (Rogers RO 4003 with $\varepsilon_r = 3.55$, substrate height b = 508µm, metallization thickness t = 35µm), the via holes and their distances are chosen as a = 4.352mm, d =

0.944mm and p = 1.887mm, respectively, according to [1]. A different substrate material (Roger RT 5870 with ε_r = 2.33, same substrate and metallization thickness as the SIW) is selected for the microstrip line, which leads to a 50Ω line width of w_{ms} = 1.577mm. These parameters are identical for all SIW-to-microstrip couplers presented in this paper. The remaining design-specific dimensions are listed in Table I.

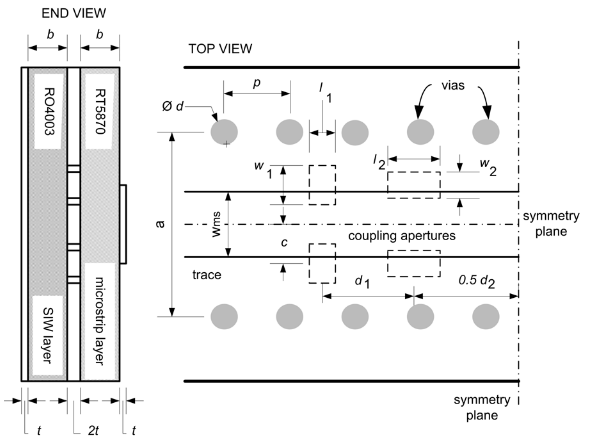


Fig. 3. Design parameters of SIW-to-microstrip couplers.

The design of a coupler (e.g. Fig. 2a) proceeds with finding the dimensions of a single rectangular aperture according to [7], [8], assuming that each slot within a number n of apertures contributes to $1/n$ of the specified overall coupling. The center-to-center spacing between apertures can then be set to a quarter wavelength with optimization finding the final individual slot and distance parameters. Alternatively, the influence of neighbouring slots can be initially taken into account using the method presented in [9].

Dual-slot couplers (Fig. 2b) are designed similarly. The only difference is the location of the slots with respect to the center of the entire structure. The parameter c in Fig. 3 is chosen to be equal to one-quarter of the width of the waveguide channel ($c = (a\text{-}d)/4$). Of course, all couplers are symmetric with respect to the symmetry plane (Fig. 3) and, therefore, only one half of the slot dimensions are listed in Table I.

III. Results

Following the above procedure, a 1dB coupler with eight single slots is designed as the first example. Since tight coupling is expected to have the most frequency-sensitive performance, this case is also chosen as verification of the design process within the HFSS environment.

Fig. 4 shows the coupler performances as obtained with HFSS and CST. The agreement is excellent and thus validates the design procedure. As expected the bandwidth around 1dB coupling, which is centered at 31.5 GHz, is fairly narrow (P_1/P_3) with return loss (RL) and isolation (P_1/P_4) values better than about 20 dB. The SIW through port is denoted as the ration of P_1/P_2. Return losses seen into the microstrip line (e.g. RL at port 3) are in a similar range and not shown here. Note that the power balance at midband frequency indicates losses of approximately 1 dB. This appears to be due to the tight coupling, which indicates that not all power radiating out from the SIW through the slots is actually captured by the microstrip line. This power loss is slightly weaker at reduced coupling levels, but a certain loss due to radiation appears to be unavoidable in direct SIW-to-microstrip couplers as demonstrated in the following design examples. It indicates that in addition to predominantly dielectric losses, not all power radiating out from the SIW through the slots is actually captured by the microstrip line.

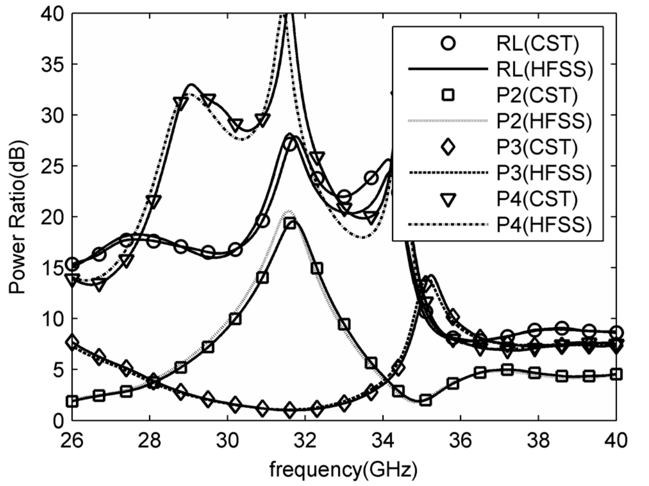


Fig. 4. Performance comparison between HFSS and CST at the example of a 1dB SIW-to-microstrip coupler with 8 single apertures (c.f. Table I).

Fig. 5 shows the performance of an 8dB coupler with 8 single slots. Return loss and isolation are better than 15 dB for most of the band (except for around 36 GHz), and the coupling behaviour is fairly constant over the entire Ka-band. Note that in this and the previous design, the distance between apertures has been kept constant as shown in Table I.

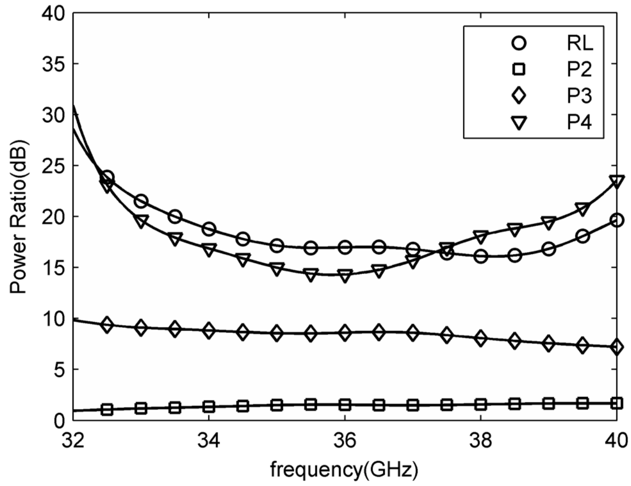


Fig. 5. Performance of 8dB SIW-to-microstrip coupler with 8 single apertures (c.f. Table I).

For comparison with Fig. 5, Fig. 6 shows the performance of a 6dB coupler design with eight dual apertures, e.g. [10], for which not only the aperture dimensions but also the lengths between them have been optimized. Although the coupling is not quite as constant due to the slightly increased coupling compared to Fig. 5, return loss and isolation have been improved.

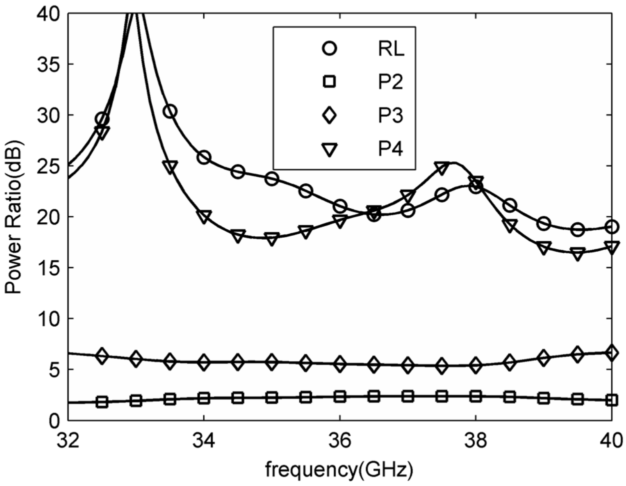
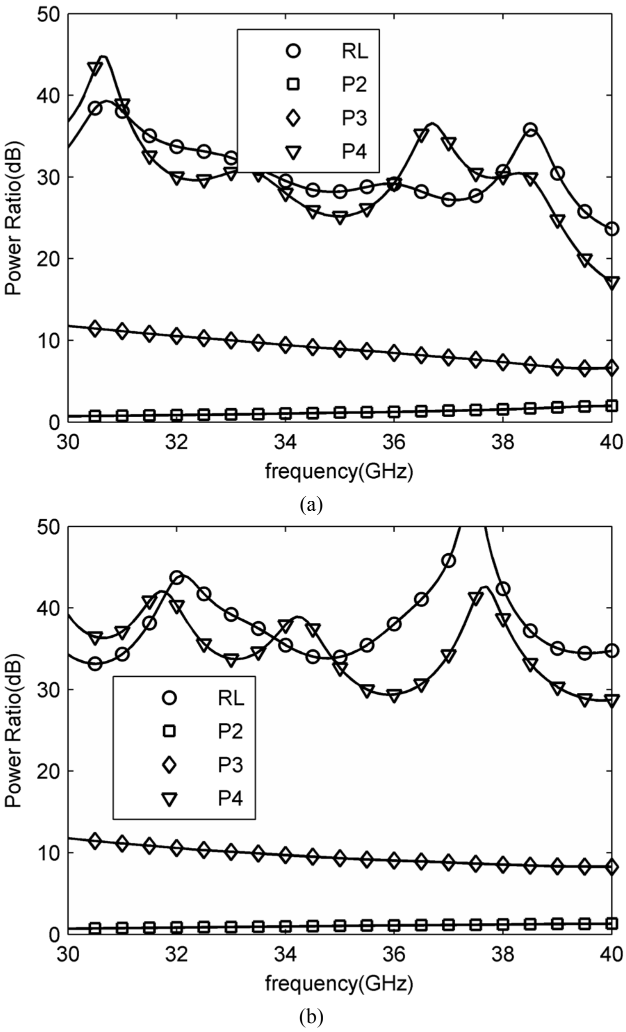


Fig. 6. Performance of 6dB SIW-to-microstrip coupler with 8 double apertures (c.f. Table I).



(a)

(b)

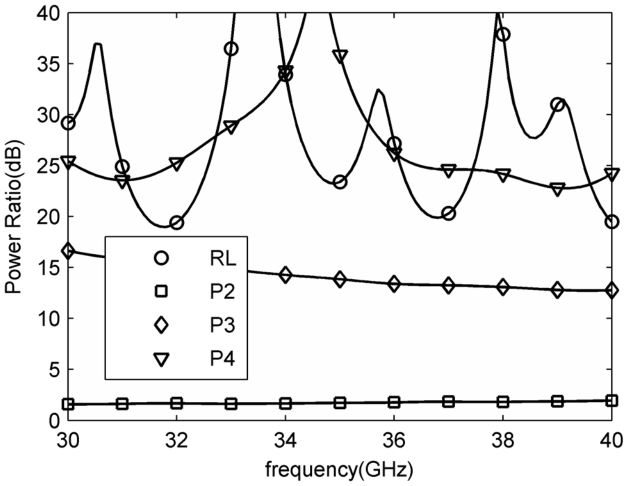
Fig. 7. Performances of 10 dB SIW-to-microstrip couplers with 4 (a) and 8 (b) double apertures (c.f. Table I).

TABLE I
DIMENSIONS (IN MM), COUPLING AND CONFIGURATIONS OF COUPLERS

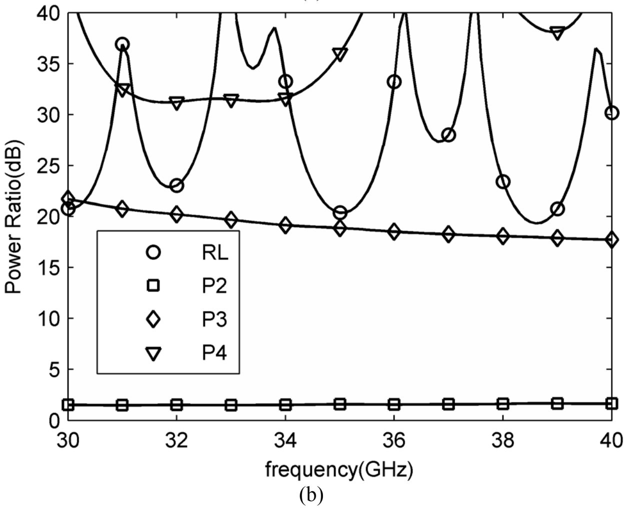
Fig.	Coupling Configuration	Dimensions		
		Length	Width	Spacing
4	1 dB, Single, $n = 8$	$l_1 = 0.766$ $l_2 = 1.190$ $l_3 = 0.746$ $l_4 = 0.997$	$w_1 = 1.045$ $w_2 = 1.580$ $w_3 = 1.913$ $w_3 = 1.806$	$d_1 = 1.550$ $d_2 = 1.550$ $d_3 = 1.550$ $d_4 = 1.550$
5	8 dB, Single, $n = 8$	$l_1 = 1.031$ $l_2 = 0.624$ $l_3 = 0.486$ $l_4 = 0.491$	$w_1 = 0.862$ $w_2 = 0.878$ $w_3 = 1.292$ $w_3 = 1.052$	$d_1 = 1.550$ $d_2 = 1.550$ $d_3 = 1.550$ $d_4 = 1.550$
6	6 dB, Double, $n = 8$, $c = 0.852$	$l_1 = 0.425$ $l_2 = 0.906$ $l_3 = 0.223$ $l_4 = 1.079$	$d_1 = 1.602$ $d_2 = 2.236$ $d_3 = 1.757$ $d_4 = 1.594$	$d_1 = 1.602$ $d_2 = 2.236$ $d_3 = 1.757$ $d_4 = 1.594$
7a	10 dB, Double, $n = 4$, $c = 0.852$	$l_1 = 0.167$ $l_2 = 0.785$	$w_1 = 1.447$ $w_2 = 1.102$	$d_1 = 1.566$ $d_2 = 1.766$
7b	10 dB, Double, $n = 8$, $c = 0.852$	$l_1 = 0.186$ $l_2 = 0.169$ $l_3 = 0.112$ $l_4 = 1.027$	$w_1 = 1.029$ $w_2 = 1.257$ $w_3 = 1.380$ $w_3 = 0.688$	$d_1 = 1.550$ $d_2 = 1.550$ $d_3 = 1.550$ $d_4 = 1.550$
8a	15 dB, Single, $n = 8$	$l_1 = 0.644$ $l_2 = 0.320$ $l_3 = 1.019$ $l_4 = 0.190$	$w_1 = 0.644$ $w_2 = 1.063$ $w_3 = 0.668$ $w_3 = 1.171$	$d_1 = 1.694$ $d_2 = 1.463$ $d_3 = 1.670$ $d_4 = 1.305$
8b	20 dB, Single, $n = 8$	$l_1 = 0.468$ $l_2 = 0.183$ $l_3 = 1.195$ $l_4 = 0.273$	$w_1 = 0.717$ $w_2 = 0.817$ $w_3 = 0.588$ $w_3 = 1.014$	$d_1 = 1.563$ $d_2 = 1.497$ $d_3 = 1632$ $d_4 = 1.300$
9	3 dB, Double, $n = 16$, $c = 0.852$	$l_1 = 0.352$ $l_2 = 0.483$ $l_3 = 0.344$ $l_4 = 0.597$ $l_5 = 0.889$ $l_6 = 1.003$ $l_7 = 0.831$ $l_8 = 0.888$	$w_1 = 1.699$ $w_2 = 1.672$ $w_3 = 1.488$ $w_4 = 1.463$ $w_5 = 1.817$ $w_6 = 1.488$ $w_7 = 2.056$ $w_8 = 1.833$	$d_1 = 1.699$ $d_2 = 1.672$ $d_3 = 1.488$ $d_4 = 1.463$ $d_5 = 1.817$ $d_6 = 1.488$ $d_7 = 2.056$ $d_8 = 1.833$
10b	15 dB, Double, $n = 8$, $c = 1.07$	$l_1 = 1.008$ $l_2 = 0.246$ $l_3 = 1.165$ $l_4 = 1.197$	$w_1 = 0.685$ $w_2 = 0.276$ $w_3 = 0.538$ $w_4 = 0.435$	$d_1 = 2.256$ $d_2 = 1.723$ $d_3 = 1.751$ $d_4 = 2.250$

The performance of a 10dB coupler with only four dual apertures is presented in Fig. 7a. Due to the small number of slots, the coupling (P_1/P_3) increases slightly but steadily across the band. However, return loss and isolation values of 25 dB or better are obtained for almost all of the Ka-band (up to 39 GHz). Fig. 7b shows the performance of the same coupler but with eight dual slots. As a result of the extended number of apertures, the coupling behaviour is flatter, and the return loss and isolation are pushed above 28 dB.

The respective performances 15 dB and 20 dB couplers are shown in Fig. 8a,b. Due to the constant number of slots (eight), the coupling (P_1/P_3) increases slightly but steadily across the band. Return loss (RL) and isolation (P_1/P_4) values of 20 dB or better are obtained.



(a)



(b)

Fig. 8. Performances of 15 dB (a) and 20 dB (b) SIW-to-microstrip couplers with eight apertures (c.f. Table I).

Fig. 9 addresses applications as wideband power splitter between the SIW and the microstrip line and shows the performance of such a component with 16 dual apertures. Due to the large number of coupling slots, return loss and isolation are close to the 20dB level. However, the power splitting occurs not at 3 dB but at 4 dB which indicates, similar to previous observations, a loss of power of approximately 1 dB.

In order to suggest a method to reduce the power loss, we propose a coupling structure in which the SIW is coupled to another SIW, which is then interfaced with microstrip circuitry using standard SIW-to-microstrip transitions [11]. Such an option is presented for a 15dB dual-aperture coupler in Fig. 10a.

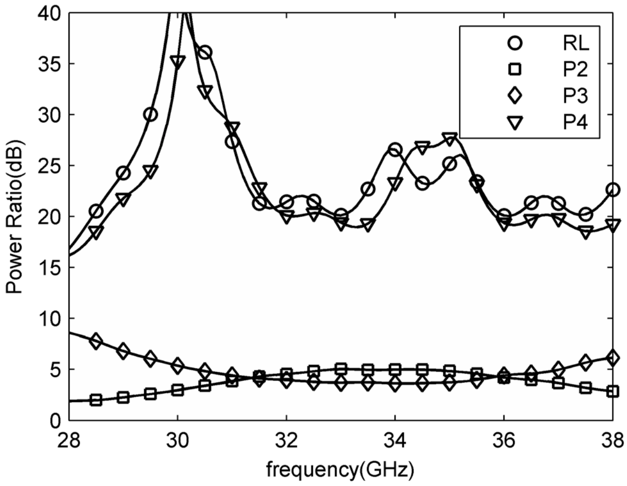
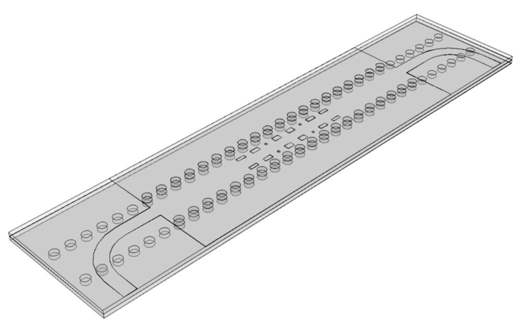
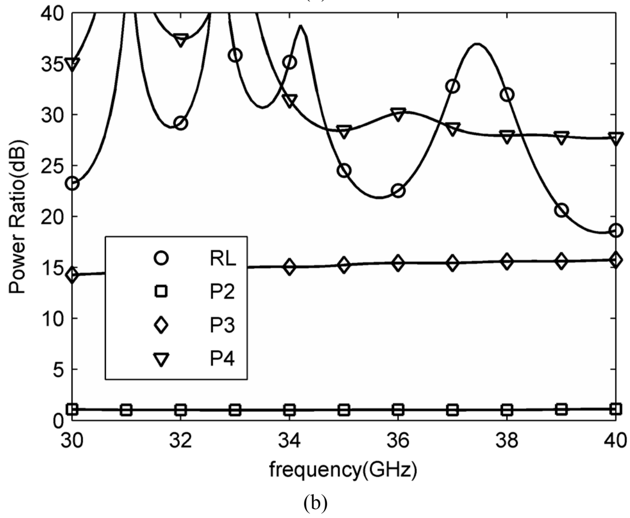


Fig. 9. Performance of 3dB SIW-to-microstrip coupler with 16 double apertures (c.f. Table I).


(a)



(b)

Fig. 10. Layout (a) and performance (b) of a 15 dB SIW-to-SIW-to-microstrip coupler with eight dual apertures.

For the SIW-to-SIW-microstrip coupler, the SIW parameters are: Rogers RT duroid/5880 substrate with $\varepsilon_r = 2.2$ and height b = 508µm; via-hole diameter d = 1.12mm, centre-to-centre via spacing p = 2.032mm; centre-to-centre via waveguide width a = 5.4mm; copper thickness t = 35µm and the air-filled coupling apertures have a thickness of 35µm. The width of the 50Ω microstrip line is 1.672mm. A SIW to microstrip transition, as depicted in Fig. 10a, has a width at the SIW junction of 1.796mm, and the length of the linear taper between these two widths is 4.639mm. See Table1 for aperture dimensions.

Compared with Fig. 8a, the losses are reduced by approximately 0.9 dB according to the data obtained at 40 GHz. Moreover, the coupling is somewhat flattened due to the use of dual instead of single apertures.

IV. Conclusions

Substrate-integrated-waveguide-to-microstrip couplers are well suited for power-monitoring and gain-control applications, especially at low (≥ 15 dB) coupling levels. Initial parameter values can be obtained from data and procedures available in the open literature. Fine optimization using an electromagnetic field solver package (e.g. HFSS or CST) completes the design. Losses due to radiation can be reduced by employing a SIW-to-SIW coupler (e.g. [2]) and adding SIW-to-microstrip transitions at the top layer. For the substrates and frequency ranges used here, insertion losses were reduced by 0.9 dB.

References

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