Broad Band Coaxial Directional Couplers for High Power Applications

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Broad-Band Coaxial Directional Couplers for High-Power Applications

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Abstract—A new class of coaxial broad-band directional couplers for high-power RF testing is presented. These devices overcome the drawbacks of classical stripline and coaxial couplers, and allow simple low-cost mechanical construction. A design technique for the new longitudinally nonuniform transversally nonsymmetrical couplers is described, providing the synthesis of any coupling shape versus frequency. As a first demonstration of the proposed method, a set of broad-band (2–7.5 GHz) low-coupling (-30, -33, -35 dB) nonsymmetrical coaxial directional couplers in air has been designed, built, and characterized, showing very good agreement between predicted and obtained performances.

Index Terms—Broad-band couplers, coaxial cables, coaxial couplers, conformal mapping.

I. INTRODUCTION

DIRECTIONAL couplers are key components in almost every microwave application requiring phase shifting, power combining and dividing, or power sampling. Coaxial directional couplers are the traditional high-power solution when bandwidth specifications are not critical [1]. Waveguide Bethe-hole couplers [2] are also used in high-power applications and many approaches have been proposed to widen their band, including multiaperture [2]–[5] and continuous-aperture [6] configurations, and narrow-wall structures [7]; unfortunately, the bands of waveguide couplers have intrinsic lower bounds because of their cutoff frequencies. Finally, stripline and microstrip directional couplers have attractive broad-band characteristics, but they are affected by significant losses and low power-handling capabilities. Two main techniques are customarily applied for the realization of broad-band strip devices. The first one is to cascade quarter-wavelength sections of uniform coupled lines [8]–[12]; this introduces step discontinuities at the interfaces between the different sections, degrading the coupler directivity. The second technique exploits continuously tapered structures [13]–[16], thus avoiding discontinuities.

Measurement applications, such as load– and source–pull systems, require both broad-band and high-power characteristics. Coaxial structures in air would be ideal for their low losses, their TEM (or quasi-TEM) field configurations ensuring zero cutoff frequency, and their high power-handling capabilities. In order to obtain coaxial structures with bandwidths competitive
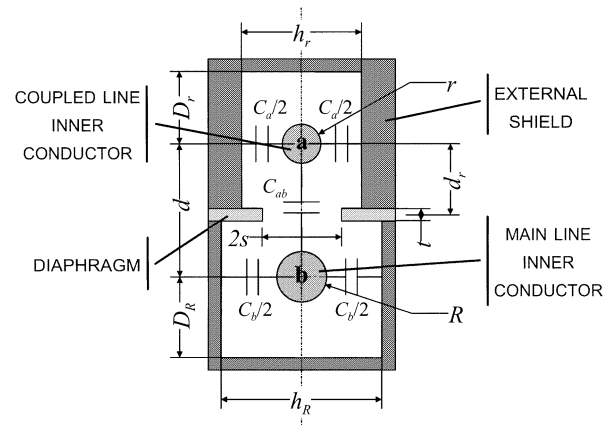
Fig. 1. Cross section of a nonsymmetrical rectangular coaxial directional coupler: dimensions and per-unit-length capacitances. The light-grey sections belong to the longitudinally nonuniform diaphragm.

with stripline and microstrip devices and presenting minimum discontinuities, it is necessary to properly design a continuous variation of the coupling factor $\mathcal{K}$ along the propagation direction z. A rather unpractical approach would be to control $\mathcal{K}(z)$ through a longitudinal variation of the distance between the inner conductors or their diameters. In these cases, the mechanical realization with a suitable degree of repeatability is difficult and expensive since it implies, e.g., the precise bending or casting of a metallic rod.

The practical solution adopted in this paper is to insert, between the two inner conductors with fixed diameter and distance, a thin metal diaphragm with a properly shaped aperture, corresponding to the desired longitudinal profile of the coupling factor. Our technique is a generalization of the approach proposed by Arndt [17], [18], and can be applied to couplers of arbitrary cross section and to any longitudinal symmetrical and nonsymmetrical $\mathcal{K}(z)$ profile. Fig. 1 shows the cross section of a transversally nonsymmetrical rectangular coaxial coupler with a diaphragm. The transversal analysis is carried out with a fast and accurate algorithm based on numerical conformal mapping (NCM) [19], providing the coupling factor and the characteristic impedances as functions of the structure dimensions. A technique derived from stripline theory [14] is then applied to the longitudinal design of the nonuniform diaphragm. The required mechanical tolerances are generally of the order of 0.1 mm, thus allowing low-cost couplers with bandwidths as large as required and excellent repeatability, since the metal diaphragm can be easily realized with accurate and inexpensive photo-etching techniques. A broad-band coupler prototype has been built and characterized (see Fig. 2), and the experimental
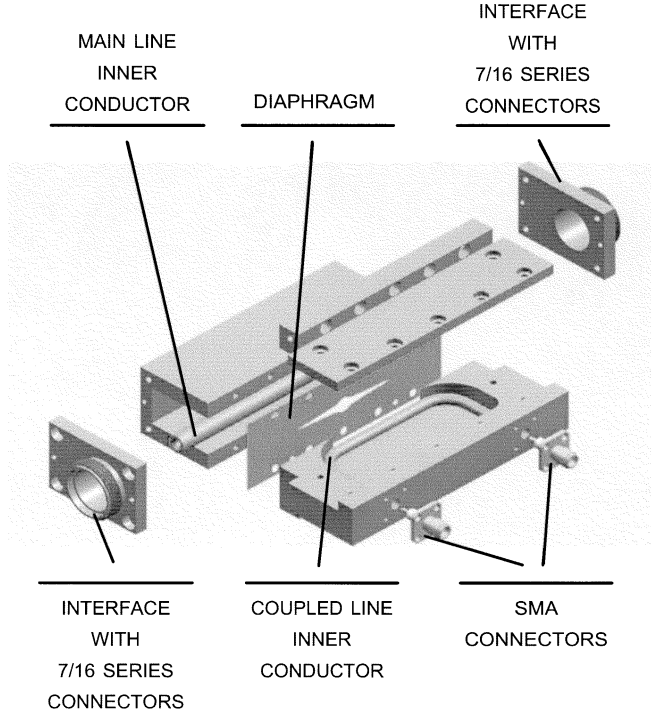
Fig. 2. Scheme of the realized coupler.

results show very good agreement with the design specifications and electromagnetic simulations.

This paper is organized as follows. Section II describes the design method applied to the new coaxial broad-band couplers and discusses some general properties of these structures. Section III introduces the nonuniform couplers that have been designed and fabricated and compares simulations with measurements. Conclusions are presented in Section IV.

II. DESIGN METHOD

Our design method for broad-band coaxial couplers is based on the quasi-static assumption that decouples the longitudinal and transversal problems. Thus, the first step of the design procedure is the evaluation of characteristic impedances or per-unit-length capacitances (for nonsymmetrical structures) as functions of the transversal geometrical parameters. This task is performed with great accuracy and at a fraction of the computational cost of other numerical techniques such as the finite-element method by the NCM code developed by Teppati *et al.* [19], which allows the study of couplers having cross sections both circular and rectangular, symmetrical and nonsymmetrical, and with and without diaphragms. In the most general nonsymmetrical case, the usual description in terms of even- and odd-mode impedances Z_e and Z_o does not hold, and one must define a capacitance matrix

$$C = \begin{pmatrix} C_a + C_{ab} & -C_{ab} \\ -C_{ab} & C_b + C_{ab} \end{pmatrix} \qquad (1)$$

where C_a, C_b, and C_{ab} are the per-unit-length capacitances shown in Fig. 1. The coupling coefficient $\mathcal{K}$ is derived from C following the classical formulation by Cristal [20, eqs. (2)–(7) and (16)–(26)].

The longitudinal design procedure adopted in this paper for nonuniform coaxial couplers is an extension of the method presented in [14] and [21] for ultra-broad-band stripline couplers. This approach has been revised, implemented in MATLAB,[1] and applied to both conventional coaxial couplers and novel structures with diaphragms. Starting from a given (arbitrary) coupling frequency profile $\mathcal{K}(f)$, this technique allows the computation of the corresponding coupling variation along the longitudinal direction $\mathcal{K}(z)$. According to [14, eq. (3.13)], the coupling $\mathcal{K}(f)$ can be written as a function of the reflection coefficient distribution $p(z)$

$$\mathcal{K}(f) = \tanh \left[\int_0^l \sin \left(\frac{4\pi f z}{v} \right) p(z)\, dz \right] \qquad (2)$$

where l is the total coupler length and v is the compensated phase velocity. Therefore, for a desired coupling function $\mathcal{K}(f)$, $p(z)$ is first computed as [14, eq. (3.15)]

$$p(z) = -\frac{4}{v} \int_0^{4\pi f_c} \sin \left(\frac{4\pi f z}{v} \right) \tanh^{-1} \left(\mathcal{K}(f) \right) df \qquad (3)$$

where f_c is the design center frequency and, hence, the coupling coefficient $\mathcal{K}(z)$ is obtained as

$$\mathcal{K}(z) = \frac{\exp \left(4 \int_0^z p(z)\, dz \right) - 1}{\exp \left(4 \int_0^z p(z)\, dz \right) + 1}. \qquad (4)$$

The aim of the longitudinal design procedure is to build an approximation $\mathcal{K}^v(z)$ of the target coupling function $\mathcal{K}(z)$ by varying along z a geometrical parameter q (e.g., the diaphragm aperture s or the distance d between the inner conductors). The optimum $q(z)$ function is found by minimizing the difference between $\mathcal{K}^v(q(z))$ and the target coupling profile

$$q^{\mathrm{opt}}(z) = \min_q \left| \mathcal{K}^v(q(z)) - \mathcal{K}(z) \right|^2 \qquad (5)$$

where $\mathcal{K}^v(q(z))$ may be computed through NCM analysis (see the examples in [19]).

It must be observed that the simultaneous maximization of the coupler directivity $\mathcal{D}$ would require the optimization of an additional geometrical parameter. For symmetrical couplers, where the condition for infinite $\mathcal{D}$ is $\sqrt{Z_e(z)Z_o(z)} = Z_r$ [20], with Z_r being an arbitrary reference impedance, this implies that the (less practical) choice of d instead of s as an optimization geometrical parameter for $\mathcal{K}$ offers at least the advantage of allowing a better $\mathcal{D}$ since the product $Z_e Z_o$ is almost independent of d.

III. DESIGN AND CHARACTERIZATION

The proposed design procedure has been applied to realize a set of three broad-band couplers in air with a nonsymmetrical rectangular cross section. The set shares the same external structure, the difference being in the aperture profiles of the thin ($t = 0.1$ mm) metal diaphragms, corresponding to coupling coefficients of -30, -33, and -35 dB, respectively, in the band between 2–7.5 GHz. The upper band limit is the maximum frequency of the 7/16 series of high-power coaxial connectors. It

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[1]MATLAB is a registered trademark of Mathworks Inc., Natick, MA.
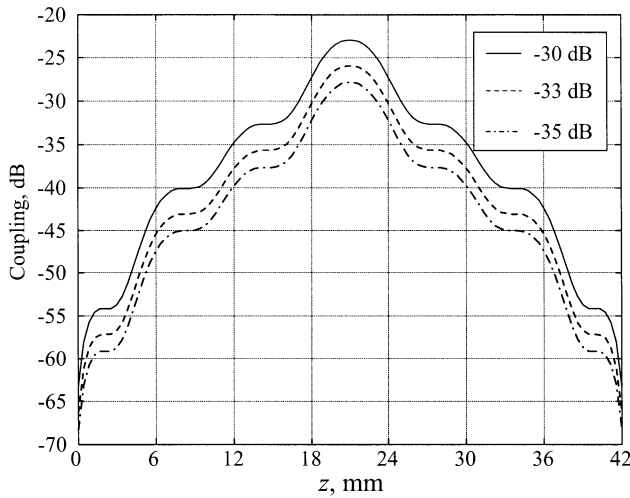
(a)
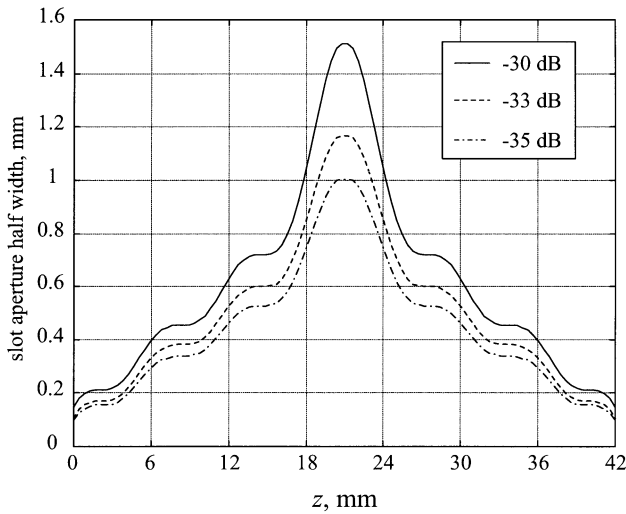
(b)

Fig. 3. (a) Target coupling factor $\mathcal{K}(z)$ and (b) designed aperture half-width $s^{\mathrm{opt}}(z)$ for the three realized couplers.
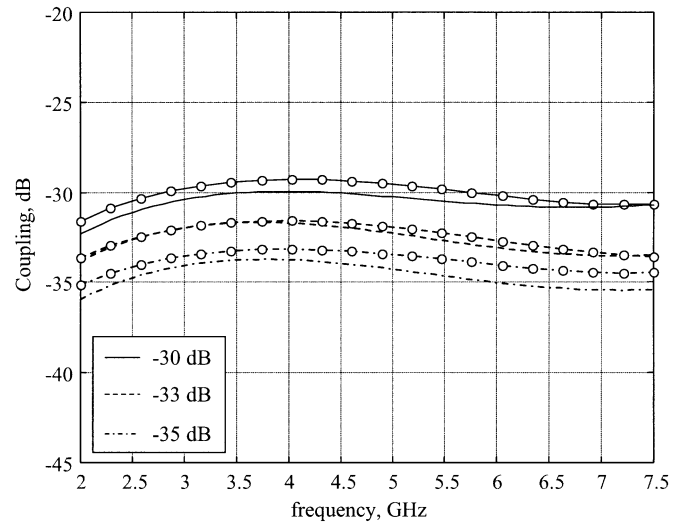

Fig. 4. Measurements (circles) and simulations of the coupling coefficient $\mathcal{K}(f)$ for the realized couplers.

The target coupling $\mathcal{K}(z)$ and the corresponding optimized aperture profiles are reported in Fig. 3 for the three coupling coefficients (-30, -33, and -35 dB at the central frequency). The MATLAB tool implementing the optimization process allows to export these profiles in a portable computer-aided design (CAD) format. The three metal diaphragms have been realized with photo-etching techniques on a 0.1-mm-thick brass sheet. Fig. 2 shows a scheme of the realized coupler. Since the coupler main line is a perfect air line, the only power limitation of the coupler is due to the connectors (the 7/16 series can handle a maximum power of approximately 100 W).

Finally, the four-port scattering parameters of the couplers have been measured with a two-port network analyzer, calibrated at the SMA ports with a short–open–load–thru (SOLT) calibration. The scattering parameters of the SMA-to-7/16 transitions needed for the connection to the main line have been measured with a short–open–load (SOL) calibration-like method, where the reference planes were moved from the SMA connector ends to the 7/16 connector ends with a deembedding technique. Fig. 4 shows the calibrated and deembedded measurements and simulation results. The measured coupling coefficient $\mathcal{K}(f)$ (circles) for the three different diaphragms is in very good agreement with the expected coupling. The measured isolation coefficient is 15 dB lower than the coupling up to 7.5 GHz.

would be possible to extend the band to frequencies lower than 2 GHz by increasing the coupler length, which has been chosen to be 42 mm. The choice of $R = 3.5$ mm allows the main coaxial line (the larger one) to be interfaced with the 7/16 connectors, thus limiting the mismatch losses. The inner conductor radius of the coupled line has been set to $r = 2$ mm, as a compromise between contrasting needs. In fact, on the one hand, interfacing the coupled line with subminiature A (SMA) connectors would require r to be equal to the standard SMA internal conductor radius (0.65 mm) in order to obtain better matching. On the other hand, the radius needs to be increased in order to grant mechanical stability and repeatability and to raise the coupling coefficient to the desired values. Also, the distance and position of the inner conductors ($d = 10$ mm and $d_r = 4$ mm) have been chosen as a compromise between higher coupling and mechanical constraints. The other dimensions ($h_r = 7.8$ mm, $h_R = 15$ mm, $D_r = 20$ mm, and $D_R = 20$ mm) grant that both the coupled and main line have 50-Ω characteristic impedance when the diaphragm aperture width is zero, assuring the impedance matching at the connector interfaces.

IV. CONCLUSION

A new class of coaxial coupling structures has been proposed and analyzed. These structures represent a significant improvement for high-power measurement systems since they have broad-band and good directivity, are easily designed, and may be fabricated at low cost with excellent repeatability. An efficient MATLAB tool for the complete design of broad-band coaxial couplers has been implemented applying NCM for cross-sectional characterization and a nonuniform coupler design technique for longitudinal optimization. This tool can be exploited for coaxial coupling structures of arbitrary cross section having at least one symmetry plane. Finally, a set of

broad-band coaxial coupler prototypes has been constructed and measured, demonstrating very good agreement with simulations and confirming the validity of the proposed design method.

ACKNOWLEDGMENT

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