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Miniaturized broadband 3-dB / 90° and 180°power splitters for GPS/GNSS anti-jam systems

Mathieu Caillet, Michel Clénet, Ala Sharaiha and Yahia M. M. Antar

Defence R&D Canada – Ottawa

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Mathieu Caillet
Royal Military College of Canada

Michel Clénet
Defence R&D Canada – Ottawa

Ala Sharaiha
Rennes Institute of Electronics and Telecommunications, France

Yahia M. M. Antar
Royal Military College of Canada

Defence R & D Canada - Ottawa

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Co-author

Original signed by Michel Clénet

Michel Clénet

Approved by

Original signed by Bill Katsube

Bill Katsube
SH CNEW

Approved for release by

Original signed by Brian Eatock

Brian Eatock
Chairman DRP

Abstract

This document reports on compact broadband rat-race and branch-line hybrids designed in the 1.15-1.6 GHz frequency band using microstrip technology. Two relatively simple design techniques using a conventional unilayer fabrication process have been investigated. The technology described in this document has been specificall developed for designing antenna feeding circuits for GPS/GNSS anti-jam systems, but it can be used for other wideband applications.

A miniaturized two-section 180° hybrid using microstrip space-fillin curves has been designed and fabricated to operate between 1.15 and 1.6 GHz on an FR4 substrate. The miniaturized geometry area is 31% of the broadband two-section 180° hybrid area. The obtained performance is as good as the conventional geometry. A 3-dB coupling with maximum amplitude imbalance of less than 0.15 dB has been measured over the 1.15-1.6 GHz band. Over this frequency band, the phase variation is ± 2°. The measured insertion loss is approximately 0.9 dB, and is mainly due to the substrate loss. To further reduce the footprint of the compact hybrid and the insertion loss, a second circuit has been designed on a substrate having a higher dielectric constant and lower loss (Cer10). The area of the second circuit is 54% of the hybrid area on the FR4 substrate. The measured performance is very similar, except that the insertion loss has been reduced by about 0.4 dB.

The lumped distributed element method has been applied to miniaturize a two-section branch-line hybrid. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when considering only the width of the circuits. Over the 1.15-1.6 GHz band, the maximum coupling imbalance obtained by measurement is 1 dB, and the phase variation is 4°. Higher than expected maximum coupling imbalance has been measured because this parameter is sensitive to the impedance values of the two-section branch-line.

Résumé

Le présent document porte sur l'étude et la conception de coupleurs hybrides 180° et 90° miniatures et large bande conçus dans la bande de fréquences 1,15-1,6 GHz utilisant la technologie microruban. Deux techniques de conception relativement simples faisant appel à un processus de fabrication monocouche classique ont été étudiées. La technologie détaillée dans ce document a été développée spécialement pour la conception de circuits d'alimentation d'antennes pour les systèmes anti-brouillage GPS/GNSS, mais elle peut être utilisée pour d'autres applications large bande.

Un coupleur hybride 180° miniature à deux sections utilisant des courbes fractales microruban a été conçu et fabriqué sur un substrat FR4 pour fonctionner entre 1,15 GHz et 1,6 GHz. La surface de la géométrie miniaturisée représente 31% de la surface du circuit hybride 180° à deux sections. Les performances obtenues sont aussi bonnes que celles du

coupleur 180° classique. Un déséquilibre du couplage à 3 dB de 0,15 dB maximum a été mesuré dans la bande 1,15-1,6 GHz. Dans cette bande de fréquences, la variation de phase est de $\pm$ 2°. Les pertes d'insertion mesurées sont d'environ 0,9 dB et sont attribuable principalement aux pertes du substrat. Pour réduire encore plus la taille du coupleur hybride compact et diminuer les pertes d'insertion, un second circuit a été conçu sur un substrat ayant une constante diélectrique plus élevée et des pertes plus faibles (Cer10). La surface du second circuit représente 54% de la surface du coupleur réalisé sur le substrat FR4. Les performances mesurées sont très similaires, excepté que les pertes d'insertion ont été réduites d'environ 0,4 dB.

La méthode des éléments répartis localisés a été appliquée pour la miniaturisation d'un coupleur hybride 90° à deux sections. La surface géométrique obtenue représente 65% de la surface du coupleur hybride 90° à deux sections, 54% lorsque la largeur des circuit uniquement est prise en compte. Dans la bande 1,15-1,6 GHz, le déséquilibre du couplage à 3 dB mesuré est de 1 dB maximum, et la variation de phase est de 4°. Un déséquilibre du couplage à 3 dB plus élevé que prévu a été mesuré car ce paramètre est sensible aux valeurs d'impédance du coupleur hybride 90° à deux sections.

Executive summary

Miniaturized broadband 3-dB / 90° and 180° power splitters for GPS/GNSS anti-jam systems

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Background: Microwave hybrids, such as the branch-line and rat-race conf gurations, are important components with many applications in circuits and antenna feed systems. For example, dual-orthogonal fed circularly polarized antennas mostly employ external power divider feed networks. To achieve a circularly polarized antenna feed structure, quadrature and 180-degree hybrids as well as T-junctions and Wilkinson power dividers have been successfully used due to their ease of design. However, the power divider circuits are relatively large in size and have limited frequency bandwidth. Their size needs to be reduced and their bandwidth improved before they can be considered for use in wideband circularly polarized antennas.

Principal results: A miniaturized two-section 180° hybrid using microstrip space-f lling curves has been designed and fabricated to operate between 1.15 and 1.6 GHz on FR4 substrate. The miniaturized geometry area is 31% of the broadband two-section 180° hybrid area. The obtained performance is as good as the conventional geometry. A 3-dB coupling with maximum amplitude imbalance of less than 0.13 dB has been noted by measurement over the 1.15-1.6 GHz band. Over this frequency band, the phase variation is ± 2°. The measured insertion loss is approximately 0.9 dB, and is mainly due to the substrate loss. To further reduce the footprint of the compact hybrid and the insertion loss, a second circuit has been designed on a substrate having a higher dielectric constant and lower loss (Cer10). The area of the second circuit is 54% of the hybrid area on the FR4 substrate. The measured performance is very similar, except that the insertion loss has been reduced by about 0.4 dB.

A compact two-section branch-line hybrid has been designed by applying the lumped distributed element method. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when considering only the width of the circuits. Over the 1.15-1.6 GHz band, the maximum coupling imbalance obtained by measurement is 1 dB, and the phase variation is 4°. Higher than expected maximum coupling imbalance has been measured because this parameter is sensitive to the impedance values of the two-section branch-line.

Significance of results: The proposed broadband rat-race hybrid design is among the most compact circuits present in the literature. Only two other conf gurations have a smaller

footprint: a rat-race employing a frequency-independent coplanar waveguide phase inverter [1] has a layout that has been reduced by 75%, and a design based on artificial transmission lines [2] allowing 91% of reduction. However, these designs include plated thru holes and very thin printed lines which require a sophisticated fabrication process. The advantage of the design proposed in this work is that it uses a simple method and the circuit is very easy to fabricate. When considering a 3-dB coupling with maximum amplitude imbalance of 0.5 dB and a phase variation of 10°, the measured frequency band of the proposed rat-race design goes up to 50%.

The footprint of the proposed broadband branch-line hybrid is equivalent to the most compact circuit found in the literature. A design based on artificial transmission lines [2] allows a 73% reduction. Again, this circuit requires a sophisticated fabrication process, as opposed to the investigated design. If allowing a 3-dB coupling with maximum amplitude imbalance of 1 dB and a phase variation of 4°, the frequency band of the proposed branch-line design increases up to 47%.

The technology described in this document has been specifically developed for designing antenna feeding circuits for GPS/GNSS anti-jam systems, but it can be used for other wideband applications.

Future work: Investigation could be carried out on a recently proposed method called dual transmission lines [3]. This miniaturization technique allows for a 64% size reduction, and is as simple as the ones used in this work. Moreover, a unilayer printed circuit is required, as in the two compact hybrid presented here. Additionally, some work to reduce the imbalance coupling of the two-section branch-line hybrid would be of interest. Finally, the 90° and 180° hybrids could be integrated further using multi-layer Low Temperature Co-fired Ceramic (LTCC) technology to achieve a very compact footprint for the circuits.

Sommaire

Miniaturized broadband 3-dB / 90° and 180° power splitters for GPS/GNSS anti-jam systems

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Contexte : Les coupleurs hybrides hyperfréquences, comme la conf guration des coupleurs en anneau et en quadrature, sont des composants importants qui comptent de nombreuses applications dans les circuits et les systèmes d'alimentation d'antenne. Par exemple, les antennes à polarisation circulaire alimentées en deux positions orthogonales emploient souvent des réseaux d'alimentation comportant des diviseurs de puissance externes. Pour réaliser un réseau d'alimentation d'antenne à polarisation circulaire, les coupleurs hybrides 180° et en quadrature ont été employés avec succès, ainsi que les diviseurs de puissance Wilkinson et à jonction en T en raison de la facilité de conception. Toutefois, les diviseurs de puissance ont une taille relativement importante et ont une bande de fréquence limitée. Il est donc nécessaire de réduire leur taille et d'améliorer leur bande de fréquence avant d'envisager de les intégrer à des antennes à polarisation circulaire large bande.

Résultats : Un coupleur hybride 180° miniature à deux sections utilisant des courbes fractales microruban a été conçu et fabriqué sur un substrat FR4 pour fonctionner entre 1,15 GHz et 1,6 GHz. La surface de la géométrie miniaturisée représente 31% de la surface du circuit hybride 180° à deux sections. Les performances obtenues sont aussi bonnes que celles du coupleur 180° classique. Un déséquilibre du couplage à 3 dB de 0,15 dB maximum a été mesuré dans la bande 1,15-1,6 GHz. Dans cette bande de fréquences, la variation de phase est de ± 2°. Les pertes d'insertion mesurées sont d'environ 0,9 dB et sont attribuable principalement aux pertes du substrat. Pour réduire encore plus la taille du coupleur hybride compact et diminuer les pertes d'insertion, un second circuit a été conçu sur un substrat ayant une constante diélectrique plus élevée et des pertes plus faibles (Cer10). La surface du second circuit représente 54% de la surface du coupleur réalisé sur le substrat FR4. Les performances mesurées sont très similaires, excepté que les pertes d'insertion ont été réduites d'environ 0,4 dB.

La méthode des éléments répartis localisés a été appliquée pour la miniaturisation d'un coupleur hybride 90° à deux sections. La surface géométrique obtenue représente 65% de la surface du coupleur hybride 90° à deux sections, 54% lorsque la largeur des circuit uniquement est prise en compte. Dans la bande 1,15-1,6 GHz, le déséquilibre du couplage à 3 dB mesuré est de 1 dB maximum, et la variation de phase est de 4°. Un déséquilibre du couplage à 3 dB plus élevé que prévu a été mesuré car ce paramètre est sensible aux valeurs d'impédance du coupleur hybride 90° à deux sections.

Portée des résultats : La configuration proposée pour le coupleur hybride 180° large bande fait partie des géométries les plus compactes parmi les circuits présents dans la littérature. Il n'y a que deux autres configurations qui ont une taille plus faible : un coupleur hybride 180° employant un inverseur de phase en ligne coplanaire indépendant de la fréquence [1] a une taille réduite de 75% ; une conception basée sur des lignes de transmission artificielles [2] permet d'obtenir une réduction de 91%. Ces conceptions comprennent cependant des trous métallisés et des lignes microruban très fines, ce qui exige un processus de fabrication perfectionné. L'avantage de la méthode proposée dans le présent travail, est qu'elle fait appel à une méthode simple et que le circuit est très facile à fabriquer. Si un déséquilibre du couplage à 3 dB de 0,5 dB maximum et une variation de phase de 10° sont tolérés, la bande de fréquence mesurée pour le coupleur hybride 180° proposé est de 50%.

La géométrie du coupleur hybride 90° large bande proposé est équivalente à celle du circuit le plus compact que l'on peut trouver dans la littérature. Une conception basée sur des lignes de transmission artificielles [2] permet une réduction de 73%. Là encore, ce circuit requiert un processus de fabrication perfectionné par rapport à la géométrie étudiée. Si un déséquilibre du couplage à 3 dB de 1 dB maximum et une variation de phase de 4 sont acceptables, la bande de fréquences de la configuration proposée pour le coupleur hybride 90° est de 47%.

La technologie détaillée dans ce document a été développée spécialement pour la conception de circuits d'alimentation d'antennes pour les systèmes anti-brouillage GPS/GNSS, mais elle peut être utilisée pour d'autres applications large bande.

Recherches futures : Il serait intéressant d'analyser une méthode proposée récemment appelée méthode des lignes de transmission doubles [3]. Cette technique de miniaturisation permet une réduction de la taille de 64% et est aussi simple que celle utilise dans le présent travail. En outre, un circuit imprimé monocouche est requis avec cette technique, comme dans le cas des deux coupleurs hybrides compacts proposés dans le présent document. De plus, des travaux visant une réduction du déséquilibre du couplage à 3 dB pour le coupleur hybride 90° à deux sections pourraient présenter un intérêt. Enfin, les coupleurs hybrides 90° et 180° pourraient être intégrés davantage à l'aide de la technologie des céramiques à plusieurs couches cuites à faible température (LTCC) pour obtenir une taille de circuit très compacte.

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1 Introduction

Microwave hybrids, such as the branch-line and rat-race configurations, are important components with many applications in circuits and antenna feed systems. For example, dual-orthogonal fed circularly polarized antennas mostly employ external power divider feed networks. To achieve a circularly polarized antenna feed structure, quadrature and 180-degree hybrids as well as T-junctions and Wilkinson power dividers have been successfully used due to their ease of design. However, the power divider circuits are relatively large in size and have limited frequency bandwidth. Their size needs to be reduced and their bandwidth improved before they can be considered for use in wideband circularly polarized antennas.

Publications on miniaturized wideband 90-degree hybrids for various applications are numerous, as was reported most recently [2, 4, 5], but compact wideband 180-degree hybrids are less popular. Many methods have been developed to reduce the size of the rat-race hybrid. Reduced ring perimeter [6], folded lines [7], artificial transmission lines [8], periodic stepped-impedance resonator structure [9], coupled lines [10] and lumped elements [11] are miniaturization strategies employed to reduce the footprint of the microstrip rat-race hybrid. Using the same principle as of folded lines, an approach based on the use of space-filling curves have been proposed by Ghali and Moselhy [12, 13]. It allows one to greatly reduce the occupied area of hybrids using a relatively simple and symmetric structure.

Enhancement of the frequency bandwidth of the branch-line and the rat-race hybrid is also a subject of interest as the bandwidth demands of broadband applications keep increasing. Diverse approaches have been proposed to increase the bandwidth of the branch-line hybrid: addition of two half-wavelength serial branches or one serial branch and one open stub being both a half-wavelength long [14], multi-section broadband impedance transforming [15, 16], or use of mixed distributed and lumped distributed elements [11, 17]. Several techniques have been reported for the improvement in bandwidth of the rat-race hybrid: addition of a fifth port [18], use of crossovers [19, 20, 21], coplanar waveguide phase inverter [1] or vertically installed planar circuit structure [22]. However, these designs require metallic tape or bonding wires, plated thru-holes or the installation of a vertical substrate, which complicates the fabrication.

This report proposes compact broadband rat-race and branch-line hybrids using single layer printed technology in the 1.15-1.6 GHz frequency band. Two relatively simple design techniques are suggested in this work. The technology described in this document has been specifically developed for designing antenna feeding circuits for GPS/GNSS anti-jam systems, but it can be used for other wideband applications. In section 2, the configuration of the proposed compact wideband rat-race coupler is presented. The design, simulation and measurements are reviewed. Section 3 is dedicated to the implementation of the miniaturized wideband branch-line coupler. The detailed design considerations and experimental results will be presented, followed by discussion and conclusions in section 4.

2 Miniaturized broadband rat-race hybrid

A broadband miniaturized microstrip circuit designed to evenly split the power and provide 180° of phase difference between the two outputs is reported in this section. A broadband two-section 180° printed hybrid was studied first. Then, a miniaturization method based on fractal geometries [12, 23] has been proposed to reduce the size of the broadband two-section rat-race hybrid. Simulation results, prototype and characterization are presented. All simulations have been performed considering material losses. The proposed miniaturization method is applicable to larger multi-section rat-race hybrids.

2.1 Broadband two-section 180° printed hybrid

Conventional hybrids have a limited frequency bandwidth. For instance, a rat-race hybrid with equal power division has a bandwidth of about 25%. It is well known that the operating bandwidth can be greatly increased using multisection hybrids, as shown in [15] for the branch-line coupler. Thus, a two-section 180° hybrid is proposed in this work to enhance the bandwidth of the conventional rat-race. A two-section 180° hybrid consists of cascading two conventional rat-race hybrids, as shown in Figure 1 for a design on a 60-mil FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$).

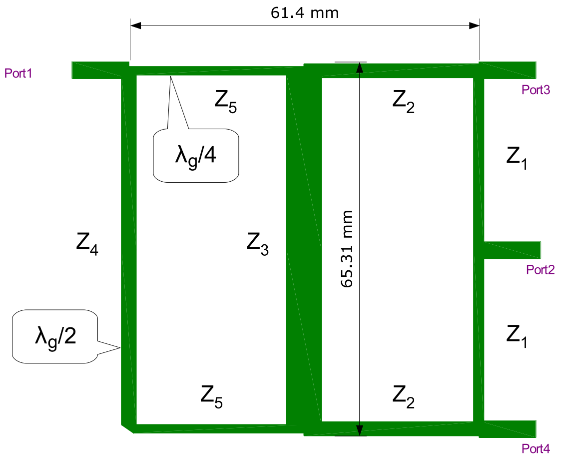
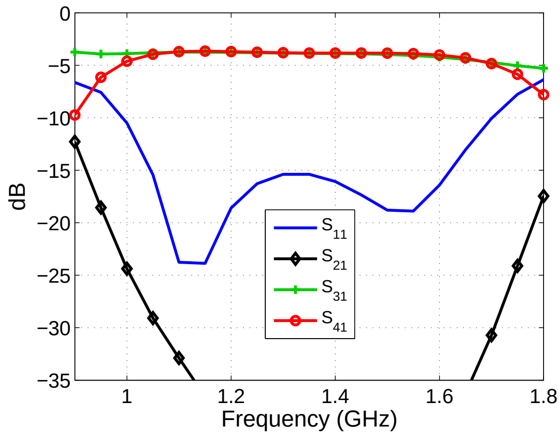


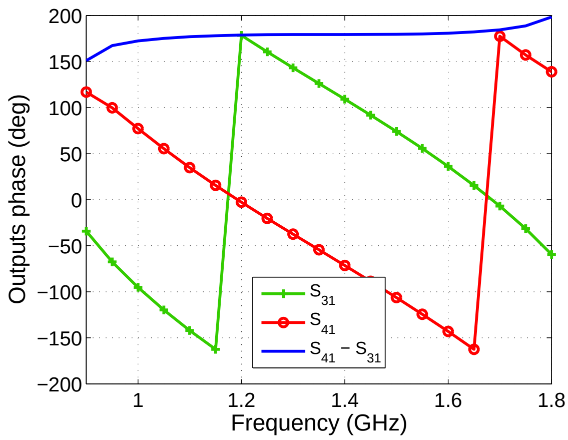
Figure 1: *Broadband two-section 180° printed hybrid on 60-mil FR4 substrate*

The broadband two-section 180° printed hybrid includes three vertical $\lambda_g/2$ and four horizontal $\lambda_g/4$ lines whose impedances Z_i are defined to have a good broadband matching. This forms a four-port network with a 180° phase shift between the two output ports. The distance between the output ports is $\lambda_g/2$. Figure 1 shows the geometry and the conventions for impedances and ports. If the input is applied to port 1, the power will be evenly split into two components with a 180° phase difference at ports 3 and 4, and port 2 will be isolated.

The hybrid could be seen as a four-port impedance transforming structure. The set of impedances Z_i has been optimized using a linear analysis tool, the circuit module of Ansoft Designer [24] in this case. The impedances required to have a good matching and balanced coupling over a 50% bandwidth are $Z_1 = 66.1\ \Omega$, $Z_2 = 56.7\ \Omega$, $Z_3 = 30.8\ \Omega$, $Z_4 = 52.9\ \Omega$, and $Z_5 = 74.1\ \Omega$ for a 50 Ω port characteristic impedance. Simulation results of S-parameters obtained on a 60-mil FR4 substrate ($\varepsilon_r = 4.4$, $tg\ \delta = 0.02$) with the dimensions of Figure 1 are presented in Figure 2(a). The electromagnetic module of Ansoft Designer has been used to achieve the simulations. The isolation (S_{21}) is greater than 35 dB between 1.15 and 1.65 GHz. Phase data are given in Figure 2(b). Between 1.15 and 1.6 GHz, a 3-dB coupling with maximum amplitude unbalance of less than 0.2 dB is obtained and the phase variation is $\pm$ 1.5° over the frequency band. The insertion losses are in the range of 0.9 dB.



(a)



(b)

Figure 2: *Broadband two-section 180° printed hybrid simulation results (a) S-parameters and (b) phase outputs.*

2.2 Compact broadband 180° printed hybrid

The space-filling curves method has been considered to reduce the size of the conventional rat-race hybrid. In [13], three space-filling curves, falling into the family of the fractal geometries, were compared for the design of compact hybrids. These curves are Moore, Sierpinski, and Minkowski constructions. Minkowski's curves are limited to the first iteration because the number of segments is very high in the case of the 2nd and 3rd iterations. The footprint of Sierpinski's curves is a little bit larger than Moore's. Thus, Moore's curves allow the best reduction in area and have been selected here to reduce the size of the rat-race hybrid. The second iteration of the Moore's geometry has been applied to each of the two sections of the broadband 180° hybrid to reduce its size.

2.2.1 Moore 2nd-iteration conventional rat-race hybrid

A compact conventional rat-race hybrid has been previously investigated in [23] using the Moore 2nd-iteration space-filling curve. Design information and results are reported here for comparison purposes.

This hybrid coupler has been implemented on a 30-mil FR4 substrate ($\varepsilon_r = 4.4$, $\tan\delta = 0.02$) to obtain a reasonable width for the microstrip lines, which is required to build the fractal geometry without additional quarter-wave transformers. The Moore 2nd-iteration space-filling curve includes 68 segments, and the length of a segment has been set to 2.6 mm. The widths of 50 and 70.7 Ω lines for the selected substrate are 0.77 mm and 1.45 mm, respectively.

A prototype has been fabricated (Fig. 3), and the measured results for magnitude and phase are shown in Figure 4. From 1.15 to 1.6 GHz, the maximum magnitude difference between the two outputs is 1 dB, and the phase difference varies by 22° (from 192° to 170°).

2.2.2 Design and simulations

To miniaturize the two-section 180° hybrid from Section 2.1, the vertical $\lambda_g/2$ and horizontal $\lambda_g/4$ lines can be taken from the compact rat-race hybrid described in Section 2.2.1. As shown in Figure 5(a), the fractal section AB corresponds to a length of $\lambda_g/4$, and the fractal section AA' is $\lambda_g/2$ long. Two AB and one AA' fractal lines are connected together to build the first section of the hybrid, with respective impedances Z_4 and Z_5 (Fig. 5(b)). The same procedure is applied to shape the second section of the two-section rat-race composed of sections of impedance Z_1 and Z_2 (Fig. 5(c)). Finally, the central line of impedance Z_3 has to be inserted to complete the implementation of the design. Due to the relatively low impedance ($Z_3 = 30.8\ \Omega$), and the resulting wide line, the meandering has been spread using all the room in the middle of the two sections. Figure 5(d) shows the complete circuit. The ports are placed in the same way as the wideband two-section rat-race hybrid.

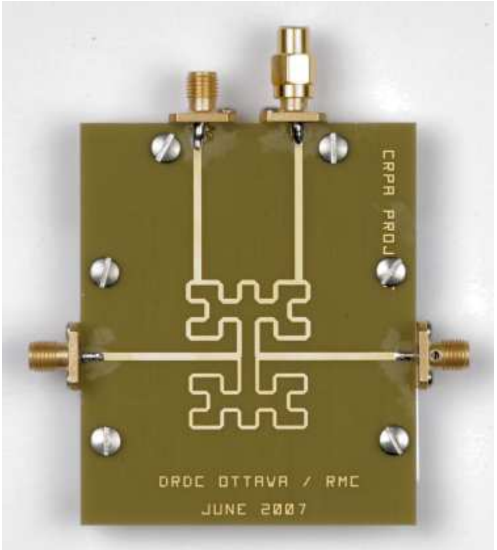


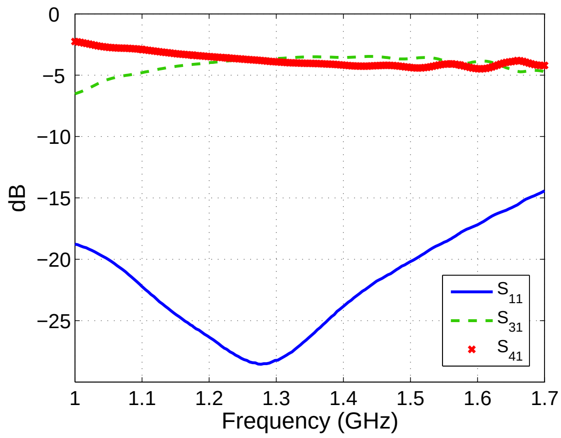
Figure 3: *Fabricated Moore 2nd-iteration rat-race hybrid on 30-mil FR4 substrate. Horizontal size of the board: 63.5 mm (2.5 in.)*

Planar EM simulation results of the broadband compact rat-race hybrid obtained on a 30-mil FR4 substrate are presented in Figure 6. The designed coupler is 43.5 mm long and 33.1 mm wide. The return loss is greater than 14 dB, the isolation (S_{21}) is greater than 35 dB between 1.1 and 1.65 GHz. Over this frequency band, a 3-dB coupling with maximum magnitude imbalance of less than 0.2 dB is obtained and the phase variation is 5° over the frequency band.

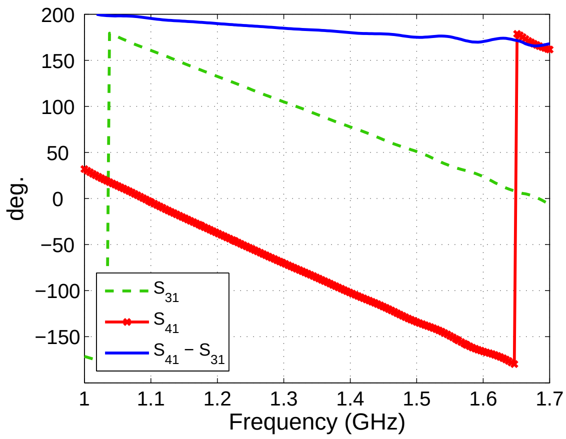
If the considered area of the hybrids is $a.b$, with a and b representing the lengths of the horizontal and vertical sides, the obtained miniaturized geometry area is 31% of the broadband two-section 180° hybrid area.

2.2.3 Fabrication and measurements

As for the miniaturized rat-race circuit described in section 2.2.1, a 30-mil FR4 substrate has been considered for building a compact broadband two-section 180° hybrid. Figure 7 presents the fabricated prototype of the broadband fractal hybrid. Experimental results demonstrate that the magnitude of the S-parameters is consistent with the simulated data (Fig. 8). The measured bandwidth def ned by a 3-dB coupling with a maximum amplitude imbalance of less than 0.5 dB is 50%, from 1.05 to 1.75 GHz. Over this frequency band, the phase variation is ± 5° (Fig. 9), the isolation is greater than 25 dB and the return loss is equal to or greater than 10 dB. Additionally, the experimental output amplitude difference is in accordance with the simulated one, having a maximum imbalance of 0.15 dB between 1.1 and 1.7 GHz. The insertion losses are in the range of 1 dB.



(a)



(b)

Figure 4: *Measured results of the Moore 2nd-iteration rat-race hybrid S-parameters: (a) magnitude and (b) phase outputs*

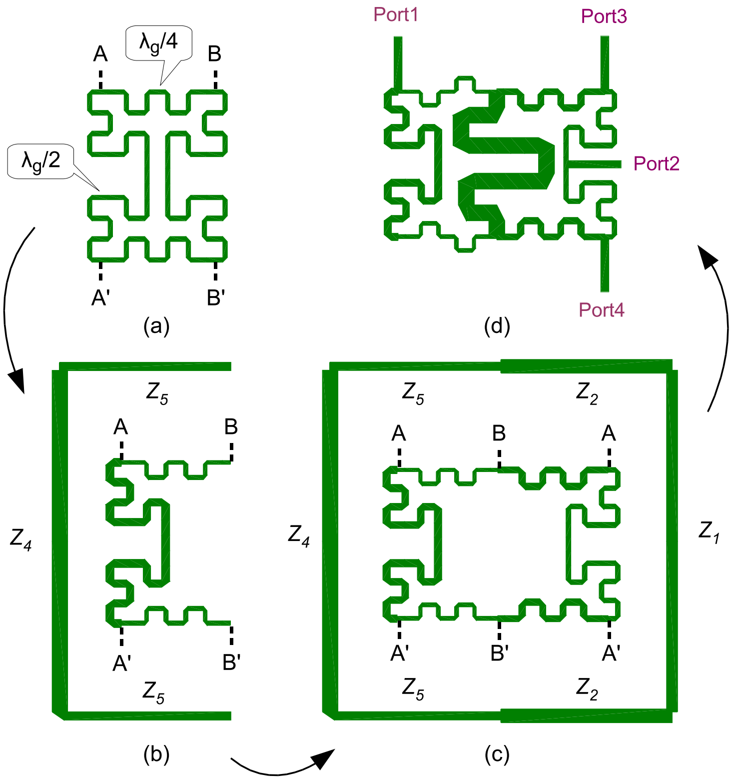
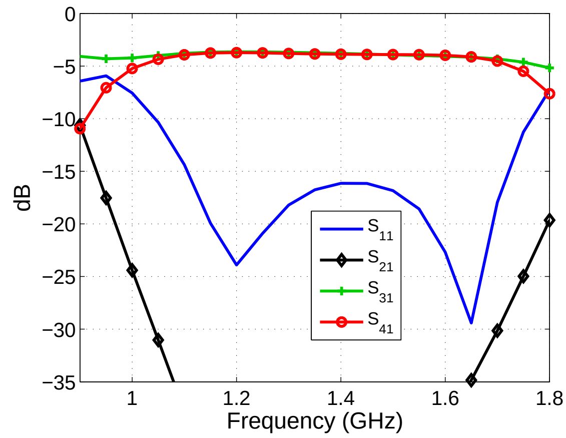
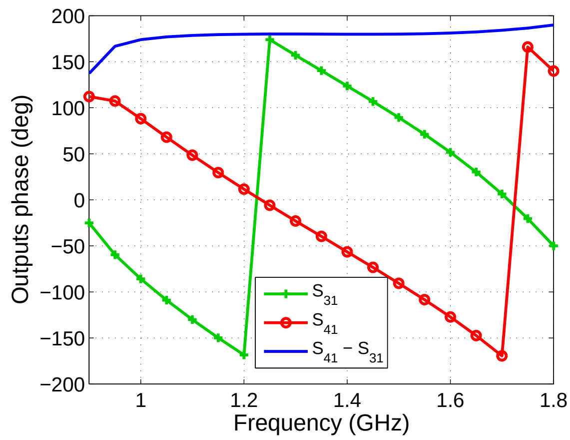


Figure 5: *Implementation of the miniaturized broadband two-section 180° hybrid from the fractal hybrid. (a) AB and AA' fractal hybrid curves are used as* $\lambda_g/4$ *and* $\lambda_g/2$ *lines, respectively. (b) The f rst section is constructed by connecting* Z_4 *and* Z_5 *lines. (c) Following the same procedure, the second section is then built by assembling* Z_1 *and* Z_2 *lines. (d) Finally, the central line* Z_3 *is meandered in the room in the middle of the two sections and ports are placed to complete the implementation.*



(a)



(b)

Figure 6: *Miniaturized broadband two-section 180° hybrid simulation results (a) S-parameters and (b) phase outputs*

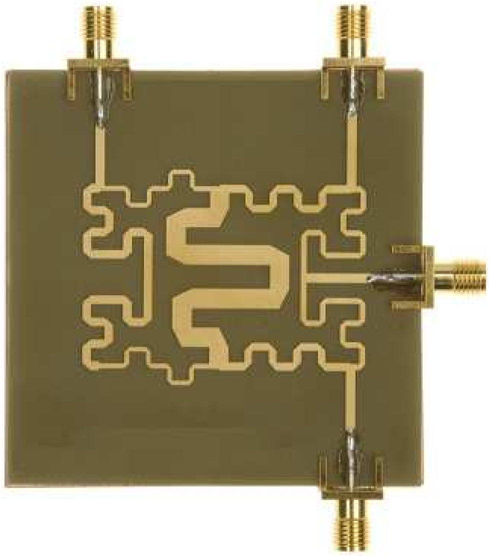


Figure 7: *Compact broadband two-section 180° hybrid prototype. Edge size of the square board: 63.5 mm (2.5 in.)*

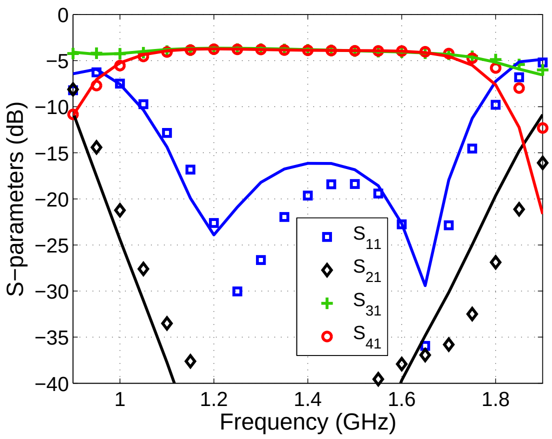


Figure 8: *Measured S-parameters of the compact broadband two-section 180° hybrid. Solid lines correspond to the simulated S-parameters, markers are for the measured results.*

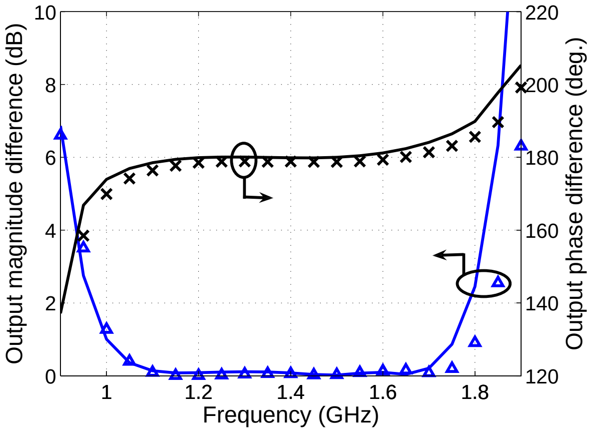


Figure 9: *Measured output magnitude and phase difference of the compact broadband two-section 180° hybrid. Solid lines correspond to the simulated S-parameters, markers represent the measured data.* $\triangle$ *mag*$(S_{41} - S_{31})$, $\times$ *angle*$(S_{41} - S_{31})$.

Detailed comparison of simulation and measured results are given in Table 1.

	Amplitude S_{31}/S_{41} (dB)		Phase diff. (°)	
	Simu.	Meas.	Simu.	Meas.
1.15 GHz	-3.79/-3.93	-3.86/-3.85	178.5	177.7
1.35 GHz	-3.74/-3.85	-3.79/-3.85	180.0	178.8
1.6 GHz	-4.07/-3.98	-4.09/-3.96	181.2	179.4

Table 1: *Comparison of simulated and measured results for the miniaturized broadband two-section 180° hybrid.*

2.2.4 Implementation on a substrate having a higher dielectric constant and lower losses

The interesting results in terms of size and performance obtained for the design of the broadband two-section 180° hybrid on the FR4 substrate encouraged the authors to try to further reduce the footprint of the hybrid. An easy solution to achieve this is to use a higher dielectric constant substrate. Furthermore, the chosen substrate has lower losses, which is also of interest to reduce the insertion losses of the broadband rat-race hybrid (in the range of 1 dB using the FR4 substrate).

Rigorously using the same design method, a two-section 180° hybrid has been designed on a 25-mil Cer10 substrate ($\varepsilon_r = 9.5$, $\tan\delta = 0.0035$). Figure 10 shows the fabricated prototype.

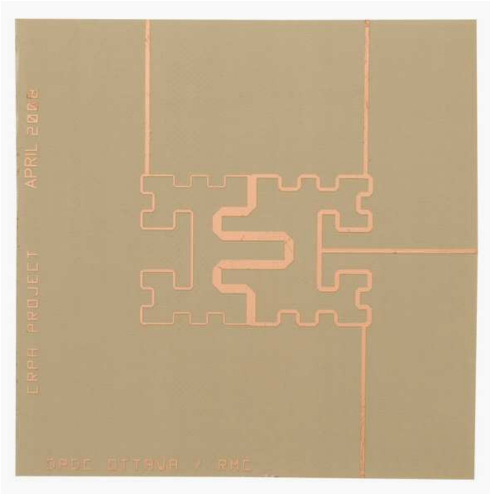


Figure 10: *Compact broadband two-section* 180° *hybrid prototype on 25-mil Cer10 substrate. Edge size of the square board: 63.5 mm (2.5 in.)*

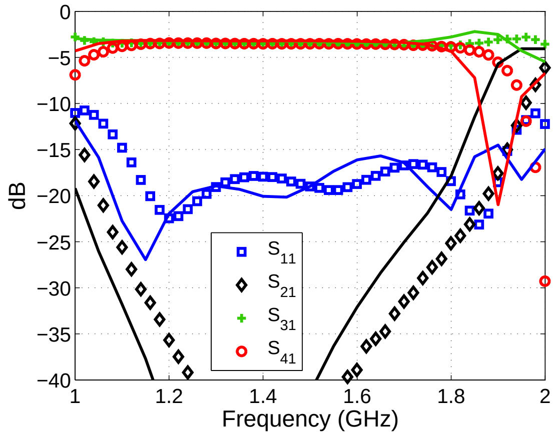
Planar EM simulation and measured results of S-parameters are presented in Figure 11(a). Output phase and amplitude difference are given in Figure 11(b). One can notice that there is a frequency shift of about 100 MHz between simulation and measurement results. This can be explained by the fact that the dielectric constant of the used substrate is quite high, and thus fabrication tolerances are increased. Also, the lines are thin, and thus more sensitive to fabrication tolerances.

Between 1.15 and 1.6 GHz, the return loss is greater than 17 dB, and the isolation is better than 30 dB. A 3-dB coupling with maximum magnitude imbalance of less than 0.1 dB is obtained and the phase variation is 3° over the frequency band.

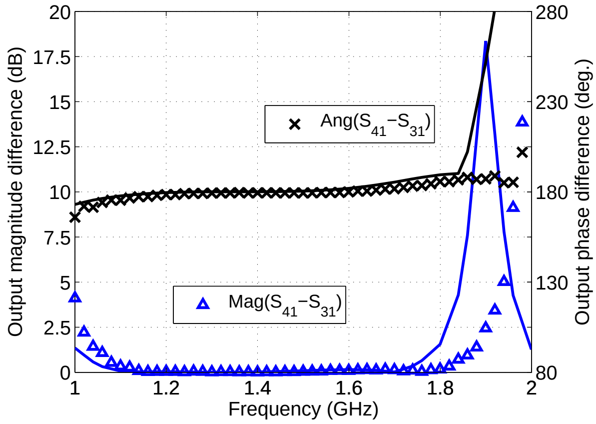
The footprint of the two-section 180° hybrid printed on the Cer10 substrate is 54% the area of the same hybrid circuit on FR4. The insertion loss is around 0.6 dB using the Cer10 substrate which is 0.4 dB lower than the design on the FR4 substrate. Thus, both the size and the insertion losses have been reduced using a substrate having a higher dielectric constant and lower loss.

2.3 Concluding remarks

A miniaturized two-section 180° hybrid using microstrip lines has been designed to operate between 1.15 and 1.6 GHz on FR4 substrate. To miniaturize this circuit, the 2nd-iteration Moore's space-f lling curve has been used. The miniaturized geometry area is 31% of the broadband two-section 180° hybrid area. The obtained performances are as good as the conventional geometry. A 3-dB coupling with maximum amplitude unbalance of less than 0.15 dB has been noted by measurement over the 1.15-1.6 GHz band. Over this frequency band, the phase variation is ± 1°. The measured insertion losses are in the vicinity of 1 dB.



(a)



(b)

Figure 11: *Miniaturized broadband two-section 180° hybrid on 25-mil Cer10 substrate measurement results (a) S-parameters and (b) magnitude and phase output difference. Solid lines correspond to the simulated S-parameters, markers represent the measured data.*

To further reduce the footprint of the compact hybrid and the insertion loss, a second circuit has been designed on a substrate having a higher dielectric constant and lower losses (Cer10). The area of the second circuit is 54% the area of the hybrid on the FR4 substrate. The measured performance is very similar, except that the insertion losses have been reduced to about 0.6 dB.

Figure 12 presents the two hybrid designs on the same scale allowing for direct size comparison with the broadband two-section 180° hybrid.

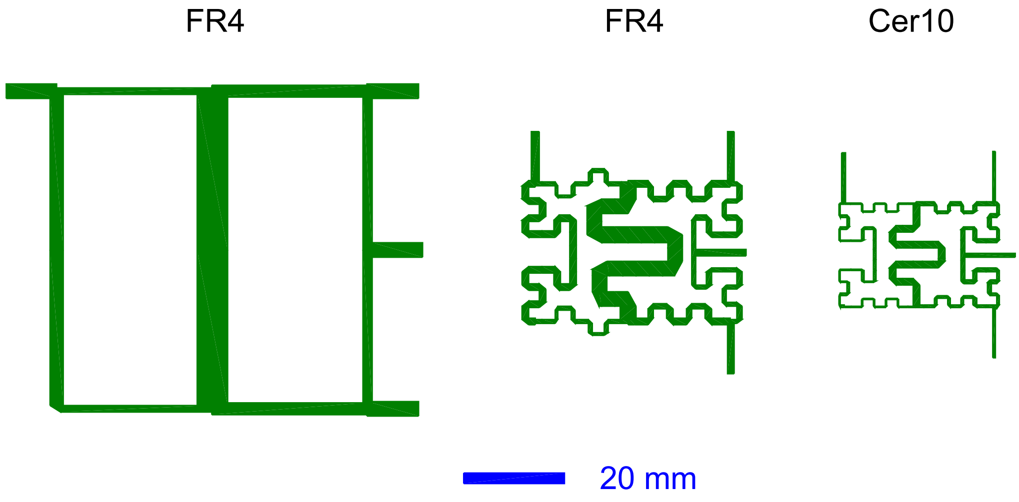


Figure 12: *Broadband 180° hybrid designs on same scale.*

3 Miniaturized broadband 90° printed hybrid

A broadband miniaturized microstrip circuit designed to evenly split the power and provide 90° phase difference between the two outputs is proposed in this section. A two-section hybrid has been investigated to enhance the frequency bandwidth response. To reduce the size of this circuit, an equivalent transmission line model including open stubs has been used as presented in [11]. Simulation results, prototype and characterization are reported here. All simulations have been performed considering material losses. The proposed miniaturization method is applicable to larger multi-section branch-line hybrids.

3.1 Broadband two-section branch-line hybrid

Conventional hybrids have a limited frequency bandwidth. For instance, a branch-line hybrid with equal power division has a bandwidth of about 15%. To increase the operating frequency band of the branch-line hybrid, a two-section geometry (Fig. 13) can been used. The impedances have been chosen from [15] to have the weakest coupling imbalance and the wider frequency bandwidth. The impedances are: $a1 = 102.88\ \Omega$, $a2 = 25.26\ \Omega$ and $b1 = 26.95\ \Omega$.

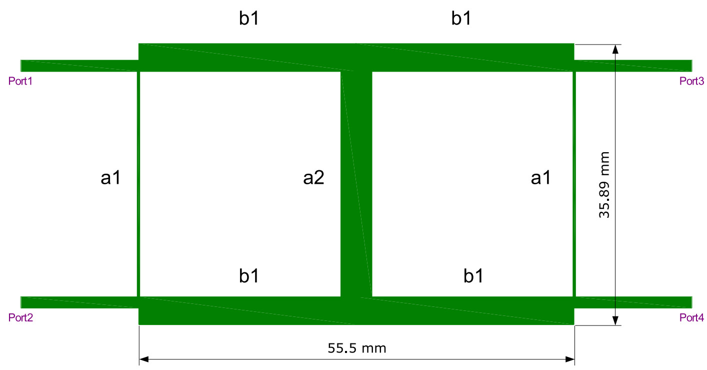
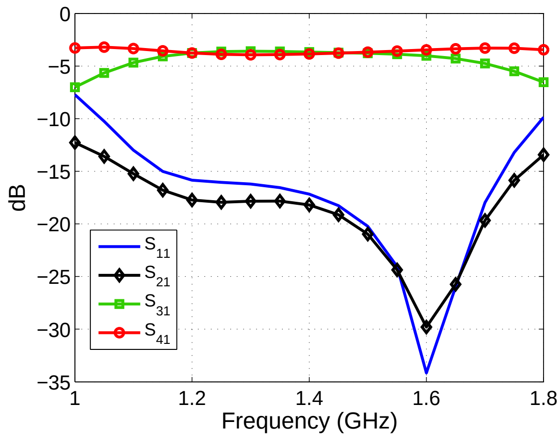


Figure 13: *Broadband two-section branch-line hybrid geometry*

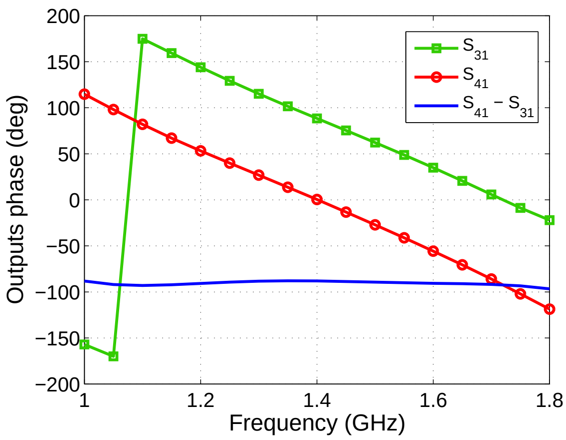
Planar EM simulation results with the geometry of Figure 13 using a 30-mil FR4 substrate are shown in Figure 14. Over the 1.15-1.6 GHz band, the maximum coupling imbalance is 0.55 dB and the phase variation is ± 2°.

A prototype has been fabricated using a 30-mil FR4 substrate with the dimensions of Figure 13, and the measured results for magnitude and phase are shown in Figure 15. From 1.15 to 1.6 GHz, the maximum magnitude difference between the two outputs is 0.6 dB, and the phase difference is 1°.

Detailed comparison of simulation and measured results are given in Table 2.



(a)



(b)

Figure 14: *Simulation results of the broadband two-section branch-line hybrid: (a) S-parameters and (b) phase outputs*

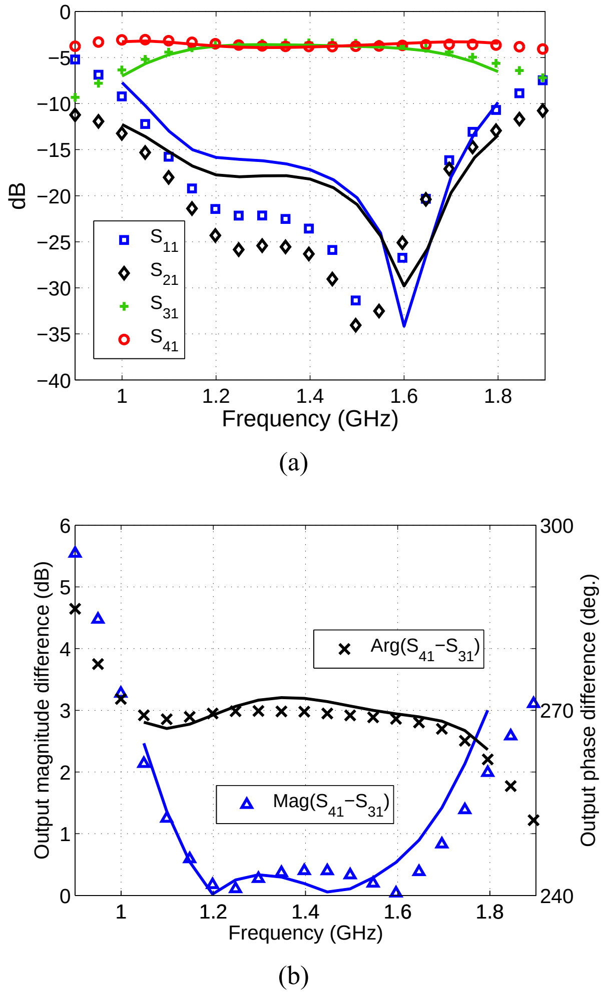


Figure 15: *Measurement results of the broadband two-section branch-line hybrid: (a) S-parameters and (b) magnitude and phase output difference. Solid lines correspond to the simulated S-parameters, markers represent the measured data.*

	Amplitude S_{31}/S_{41} (dB)		Phase diff. (°)	
	Simu.	Meas.	Simu.	Meas.
1.15 GHz	-4.08/-3.55	-3.94/-3.35	-92.2	-91.1
1.35 GHz	-3.62/-3.91	-3.43/-3.79	-87.9	-90.2
1.6 GHz	-4.02/-3.47	-3.72/-3.68	-90.6	-91.4

Table 2: *Comparison of simulated and characterized results for the broadband two-section branch-line hybrid*

Based on this geometry, the lumped distributed elements miniaturization technique described in [11] can be applied to reduce the footprint of the coupler. The design using this technique is presented in section 3.2.

3.2 Compact broadband branch-line hybrid using lumped distributed elements

The space-f lling curves method does not allow to reduce the footprint of the two-section branch-line hybrid as much as for the two-section rat-race coupler. Thus, the lumped distributed elements miniaturization technique has been selected because the size reduction is among the best throughout the different techniques enumerated in the introduction of this report. Furthermore, it is quite easy to use for designing a branch-line hybrid and the circuit fabrication requires only a conventional unilayer process, like for the design of the broadband rat-race hybrid.

The miniaturization method applied for the size reduction of the two section branch-line hybrid is f rst described in this section. The design of a compact wideband branch-line hybrid is then presented.

3.2.1 Miniaturization method

The lumped distributed elements method consists of shrinking a conventional transmission line having a Z_c characteristic impedance and a θ electrical length (Fig. 16(a)) by replacing it by a shorter transmission line, of characteristic impedance Z_s and an electrical length of θ_s, and two open stubs having a Z_{o1} characteristic impedance and a θ_{o1} electrical length (Fig. 16(b)). This represents its equivalent transmission line model.

Two design equations are needed to f nd the parameters of the equivalent transmission line [11]:

$$B_{o1} = \frac{\cos\ \theta_s - \cos\ \theta}{Z_c \sin\ \theta} \tag{3.1}$$

$$Z_s = \frac{Z_c \sin\ \theta}{\sin\ \theta_s} \tag{3.2}$$

where B_{o1} is the input admittance of the open stubs defined by

$$j\ B_{o1} = j\ \tan\ \theta_{o1}/Z_{o1}. \tag{3.3}$$

The ratio θ_s/θ represents the size reduction factor. Knowing θ, θ_s is fixed to have the desired reduction. The equivalent transmission line of Figure 16(b) is a filter, so the cutoff frequency has to be considered. The authors of [11] show that $\theta = 30°$, $\theta_s = 12.5°$ associated with 50 Ω stubs allows wideband applications as well as high cutoff frequency. Thus, the quarter-wavelength lines would be split into 3 segments.

3.2.2 Design and simulations

θ and θ_s have been chosen to be 30 and 12.5° respectively. For each horizontal microstrip line of the two-section branch-line hybrid (Fig. 13), B_{o1} and Z_s can be calculated using equations 3.1 and 3.2. From B_{o1}, the impedance and length of stubs are found using equation 3.3 and choosing Z_{o1}. The initial values of the distributed lumped elements are given in Table 3. Then, three sections are used for each quarter-wave length line. To respect the geometry of the three-branch hybrid, each two parallel stubs are combined in a single stub. Finally, the values have to be adjusted to match the desired performances.

The proposed design of the miniaturized 90° hybrid obtained on a 30-mil FR4 substrate is shown in Figure 17. Planar EM simulation results of S-parameters with the dimensions of Figure 17 are presented in Figure 18(a). Phase data are given in Figure 18(b). Over the 1.15-1.6 GHz bandwidth, a 3-dB coupling with maximum amplitude unbalance of less than 0.3 dB is obtained and the phase variation is ±1.4°. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when considering only the width of the circuits.

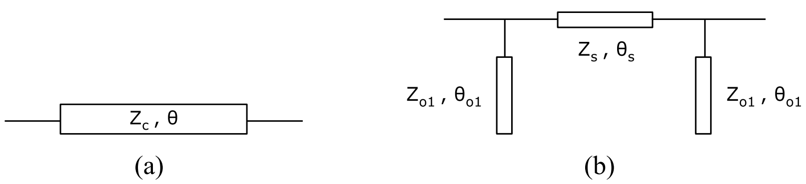


Figure 16: *Size reduction scheme using lumped distributed elements. (a) Conventional transmission line. (b) Equivalent transmission line with a series transmission line and two open stubs.*

Z_s	$62.4\ \Omega$
B_{o1}	$0.0082\ S$
Z_{o1}	$50\ \Omega$
θ_{o1}	$22.22°$

Table 3: *Choice of lumped distributed element's values for $Z_c = 26.95\ \Omega$ and $\theta = 30°$ for $\theta_s = 12.5°$.*

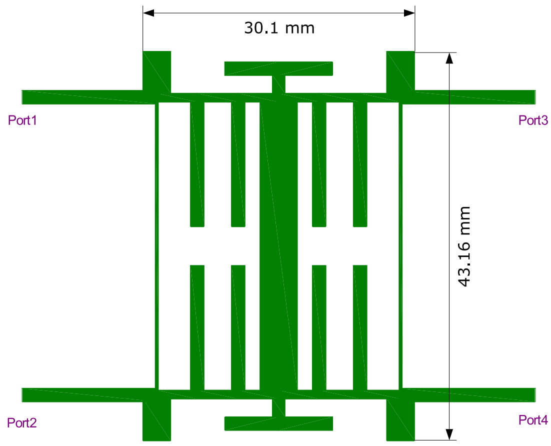
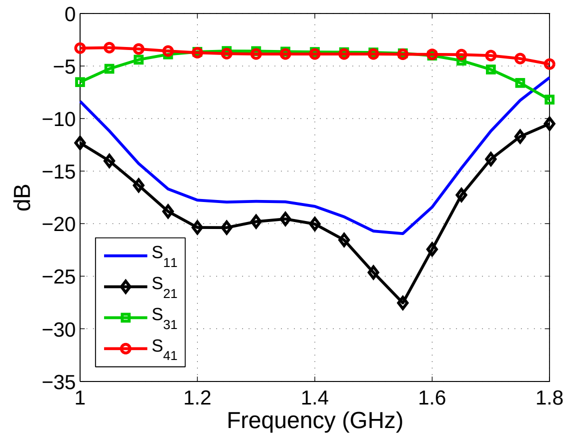
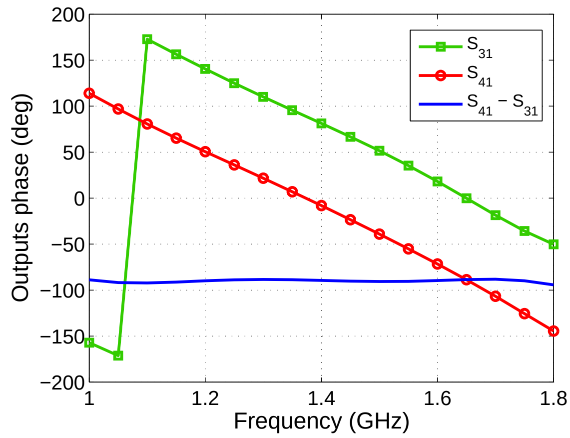


Figure 17: *Miniaturized broadband two-section branch-line hybrid geometry using a 30-mil FR4 substrate.*



(a)



(b)

Figure 18: *Simulation results of the miniaturized two-section branch-line hybrid: (a) S-parameters and (b) phase outputs.*

3.2.3 Fabrication and measurement results

As described in section 3.2.2, a 30-mil FR4 substrate was used to fabricate the proposed compact broadband branch-line hybrid. Figure 19 presents the fabricated prototype of the broadband distributed lumped elements hybrid. The measured bandwidth def ned by a 3-dB coupling with a maximum amplitude imbalance of less than 1 dB is 47%, from 1.05 to 1.7 GHz (Fig. 20(b)). Over this frequency band, the phase variation is 4°, the isolation is greater than 15 dB and the return loss is equal to or greater than 13 dB. Measurement results are reported in Fig. 20.

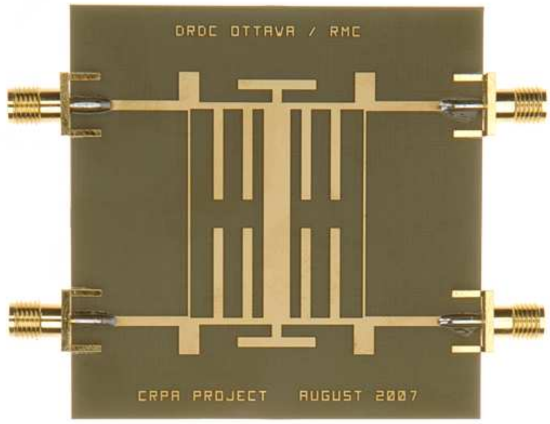
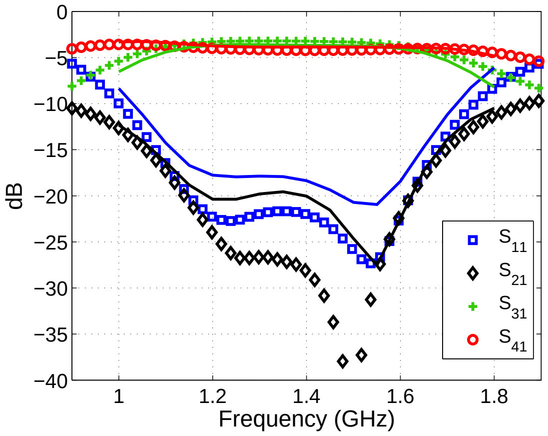


Figure 19: *Miniaturized broadband two-section branch-line hybrid prototype using a 30-mil FR4 substrate.*

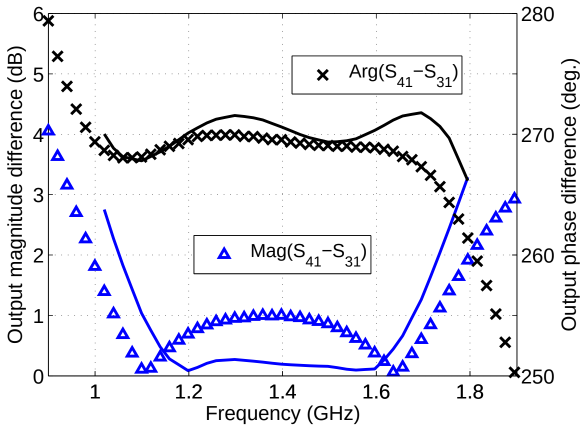
Experimental results demonstrate that the magnitude of the S-parameters is consistent with the simulated data. However, the experimental output amplitude difference is not in accordance with the simulated one, having a maximum imbalance of 1 dB between 1.15 and 1.6 GHz.

The difference between simulation and measurement of the output amplitude difference is greater than expected. This can be explained by the fact that this parameter is very sensitive to the values of the impedances in the two-section branch-line hybrid, as a parametric study shows it in Fig. 21. Moreover, the microstrip lines of the fabricated prototype have been measured (Fig. 22 and table 4) and a simulation has been carried out considering the actual dimensions of the fabricated circuit. Figure 23 shows the obtained results. One can see that the ripples of the output magnitude difference are larger than the original simulated design.

Detailed comparison of simulation and measured results are given in Table 5.

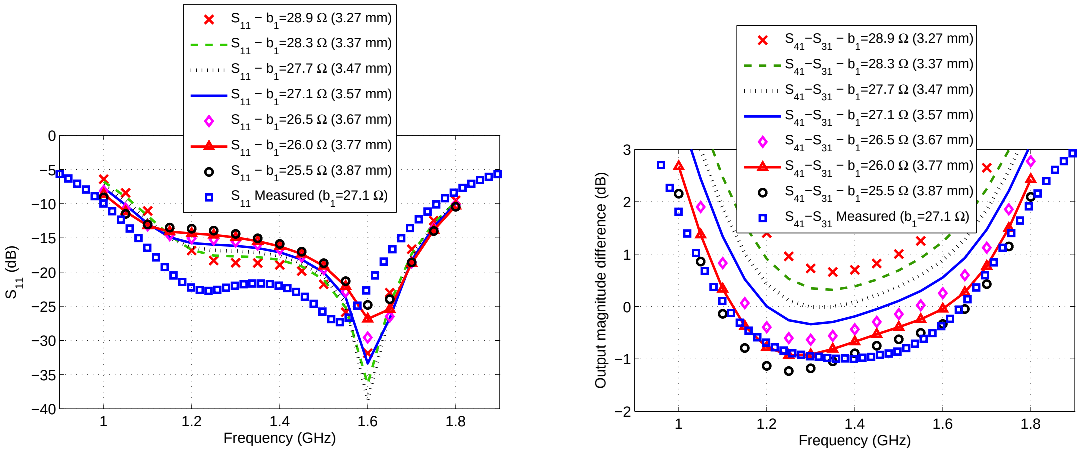


(a)



(b)

Figure 20: *Measurement results of the miniaturized two-section branch-line hybrid: (a) S-parameters and (b) magnitude and phase output difference. Solid lines correspond to the simulated S-parameters, markers represent the measured data.*



(a) (b)

Figure 21: *Simulated (a) S_{11} and (b) magnitude output difference, as a function of the b1 impedance of the two-section branch-line hybrid.*

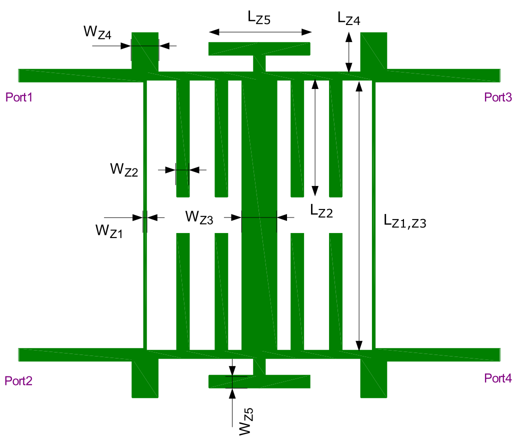


Figure 22: *Miniaturized broadband two-section branch-line hybrid parameters.*

Parameter	Designed (mm)	Fabricated (mm)
W_{Z1}	0.35	0.32
$L_{Z1,Z3}$	32.00	32.03
W_{Z2}	1.45	1.41
L_{Z2}	13.80	13.81
W_{Z3}	4.07	4.03
W_{Z4}	3.10	3.07
L_{Z4}	4.60	4.59
W_{Z5}	1.45	1.44
L_{Z5}	12	11.97

Table 4: *Comparison of designed and fabricated dimensions for the compact two-section branch-line hybrid.*

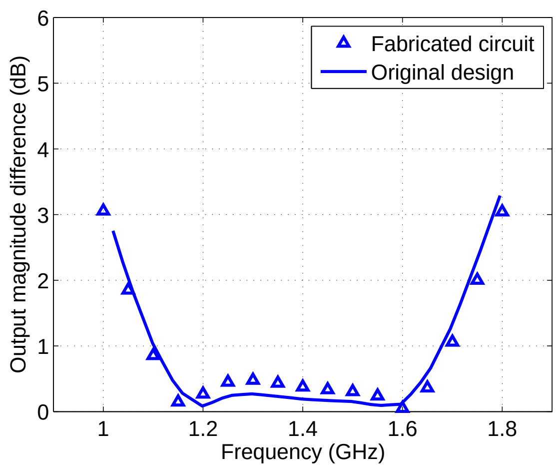


Figure 23: *Simulated magnitude output difference considering the actual dimensions of the fabricated miniaturized broadband branch-line prototype.*

3.3 Concluding remarks

Two microstrip broadband 90° hybrids have been simulated around 1.37 GHz on a 30-mil FR4 substrate using different geometries. The f rst one is the broadband two-section branch-line hybrid. The size is 56 x 36 mm^2 and the 3-dB coupling with maximum amplitude unbalance of less than 0.5 dB has been noted from 1.15 to 1.6 GHz. Over this frequency band, the phase variation is 4°.

To reduce the size, the lumped distributed element's method has been investigated. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when

	Amplitude S_{31}/S_{41} (dB)		Phase diff. (°)	
	Simu.	Meas.	Simu.	Meas.
1.15 GHz	-3.90/-3.58	-3.42/-3.88	-91.2	-91.0
1.35 GHz	-3.67/-3.87	-3.20/-4.19	-88.7	-90.0
1.6 GHz	-4.01/-3.90	-3.69/-4.06	-89.6	-91.1

Table 5: *Comparison of simulated and measured results of the compact two-section branch-line hybrid.*

considering only the width of the circuits. Over the 1.15-1.6 GHz band, the maximum coupling imbalance is 1 dB, and the phase variation is 4°. Higher than expected coupling imbalance has been measured because this parameter is sensitive to impedance variation, and therefore to the line width fabrication tolerances.

Figure 24 presents the two different designs on the same scale allowing for direct size comparison.

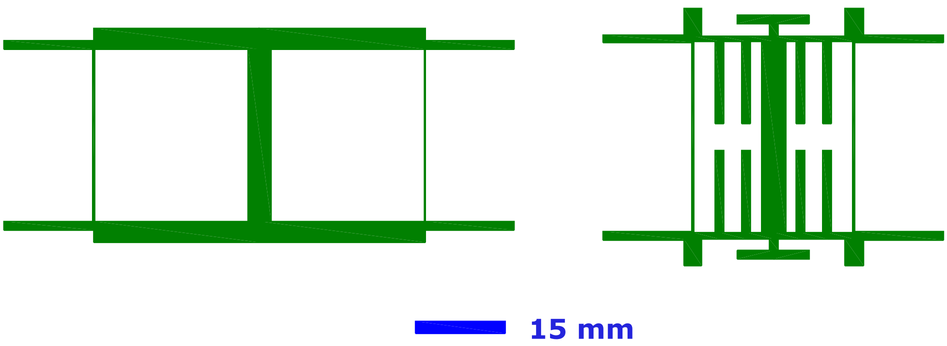


Figure 24: *Hybrid designs on same scale using 30-mil FR4 substrate.*

4 Conclusions and perspectives

This document reports on compact broadband rat-race and branch-line hybrids designed for operation in the 1.15-1.6 GHz frequency bandwidth using microstrip technology. Two relatively simple design techniques using a conventional unilayer fabrication process have been suggested. The technology described in this document has been specifically developed for designing antenna feeding circuits for GPS/GNSS anti-jam systems, but it can be used for other wideband applications.

A miniaturized two-section 180° hybrid using microstrip lines has been designed using an FR4 substrate to operate between 1.15 and 1.6 GHz. To miniaturize this circuit, the 2nd-iteration Moore's space-filling curve has been used. The miniaturized geometry area is 31% of the broadband two-section 180° hybrid area. The obtained performance is as good as the conventional geometry. A 3-dB coupling with maximum amplitude unbalance of less than 0.13 dB has been measured over the 1.15-1.6 GHz band. Over this frequency band, the phase variation is $\pm$ 1°. The measured insertion losses are about 1 dB. To further reduce the footprint of the compact hybrid and the insertion loss, a second circuit has been designed on a substrate having a higher dielectric constant and lower losses (Taconic Cer10). The area of the second circuit is 54% of the area of the hybrid on the FR4 substrate. The measured performance is very similar, except that the insertion loss has been reduced to about 0.6 dB.

The lumped distributed element's method has been applied to miniaturize a two-section branch-line hybrid. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when considering only the width of the circuits. Over the 1.15-1.6 GHz band, the maximum coupling imbalance is 1 dB, and the phase variation is 4°. However, higher than expected maximum coupling has been measured because this parameter is sensitive to impedance variation, and therefore to the line width fabrication tolerances.

Future work in miniaturization could investigate the use of the recently proposed method called dual transmission lines [3]. This miniaturization technique allows 64% size reduction, and is as simple as the ones proposed in this study. Moreover, a unilayer printed circuit is required, like the two compact hybrids presented here. Additionally, some work to reduce the imbalance coupling of the two-section branch-line hybrid would be of interest. Finally, the 90° and 180° hybrids can be integrated using a multi-layer Low Temperature Co-fired Ceramic (LTCC) technology to achieve a very compact footprint of the circuits.

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Miniaturized broadband 3-dB / 90° and 180° power splitters for GPS/GNSS anti-jam systems

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Caillet, M.; Clénet, M.; Sharaiha, A.; Antar, Y.M.M.

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This document reports on compact broadband rat-race and branch-line hybrids designed in the 1.15-1.6 GHz frequency band using microstrip technology. Two relatively simple design techniques using a conventional unilayer fabrication process have been investigated. The technology described in this document has been specifically developed for designing antenna feeding circuits for GPS/GNSS anti-jam systems, but it can be used for other wideband applications.

A miniaturized two-section 180° hybrid using microstrip space-filling curves has been designed and fabricated to operate between 1.15 and 1.6 GHz on an FR4 substrate. The miniaturized geometry area is 31% of the broadband two-section 180° hybrid area. The obtained performance is as good as the conventional geometry. A 3-dB coupling with maximum amplitude imbalance of less than 0.15 dB has been measured over the 1.15-1.6 GHz band. Over this frequency band, the phase variation is $\pm 2°$. The measured insertion loss is approximately 0.9 dB, and is mainly due to the substrate loss. To further reduce the footprint of the compact hybrid and the insertion loss, a second circuit has been designed on a substrate having a higher dielectric constant and lower loss (Cer10). The area of the second circuit is 54% of the hybrid area on the FR4 substrate. The measured performance is very similar, except that the insertion loss has been reduced by about 0.4 dB.

The lumped distributed element method has been applied to miniaturize a two-section branch-line hybrid. The obtained geometry area is 65% of the two-section branch-line hybrid area and 54% when considering only the width of the circuits. Over the 1.15-1.6 GHz band, the maximum coupling imbalance obtained by measurement is 1 dB, and the phase variation is $4°$. Higher than expected maximum coupling imbalance has been measured because this parameter is sensitive to the impedance values of the two-section branch-line.

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90° power splitter
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microstrip technology