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ABSTRACT-In recent years, the hybrid branch-line coupler has attracted much attention due to its appealing features such as of low cost and ease in fabrication for wireless communications. The fifth-generation cellular networks promise to support several wireless technologies by capitalizing a multitude of frequencies and increase data rates. To achieve that, the butler matrix technique can be used to enhance both bandwidth and data rate with the implementation of beamforming. Conventional hybrid couplers are the main component to build a butler matrix, but they are generally bulky in size and narrow in bandwidth. Moreover, requirements imposed by newer wireless technologies makes the efforts in improving size compactness and bandwidth even more challenging. On the other hand, several techniques have been proposed in literature to solve both issues. This study focuses on the design challenges and issues of hybrid coupler designs and technologies, besides underlining their promising potential. In this context, several techniques for hybrid coupler to achieve the required bandwidth and size reduction are highlighted, such as the T-shape, meander line, two sections, three-section, and parallel couple lines.

Keywords: Hybrid couplers, wideband couplers, branch-line couplers, ring couplers, rat-race couplers, power dividers.

1. INTRODUCTION

Directional couplers have been studied widely since the 1940s and implemented using transmission lines and waveguides. The 3-dB hybrid coupler, widely referred to as the hybrid coupler is an example of the directional coupler. It provides equal power division or combining with a phase difference of 90° or 180° between the output ports, depending on the design topology. It is also one of the main circuit components for designing balanced amplifiers [1]. Hybrid couplers, also known as branch-line couplers, consist of four port power dividers, with each port matched to 50 Ω impedance. When port 1 is fed, the power will be divided equally between each port with a phase difference of 90°[2]. This component combines or divides the power of the
transmitted and received RF and microwave signals while providing high isolation between the ports[3]. The main function of the hybrid coupler is to divide the power equally between the two output ports and the coupled port. There must be no power reflection back at the same input port and no power must reach to the isolation port[4][5].

Future wireless communication technologies, which use millimeter-wave and sub-millimeter wave spectra require high-speed switching to enable beamforming and the pointing of radiation towards users from a base station [6][7]. This characteristic is one of the key features of wireless connections between the base stations and mobile stations, and in point-to-point communication [8]. Thus, it is important that research is directed towards enablers of such features, which include microwave devices such as branch-line couplers [9]. Branch-line couplers can be used for several applications such as dividers and combiners, modulators and demodulators, power amplifiers, butler matrices, and antenna array feed networks. More importantly, the branch-line coupler is one of the primary and simplest components that can be used to build a butler matrix for the control of radiation in antenna networks [10][11]. Hybrid couplers are generally categorized into two types, depending on the phase difference between the two output ports: 3-dB 90° and 180°. They are typically used as 3 dB power dividers and are analyzed using even and odd modes [12]. Conventional hybrid branch-line couplers can be easily implemented using quarter wavelength transmission lines. These transmission lines can be designed in the form of horizontal and vertical arms with characteristic impedances of $Z_0 / \sqrt{2} = 35.35\ \Omega$ and $Z_0 = 50\ \Omega$, respectively [13]. To analyze the four-port symmetric network, the input wave is divided equally between the two output ports via coupling[14].

The major challenge in designing conventional (quarter wavelength) branch line couplers are their bulky size and its typically narrow bandwidths of 10% to 20% [15]. Therefore, a typical method used to enhance the bandwidth and reduce the size is the use of more sections in the branch-line coupler[16]. A T-shaped design can be used with transmission lines, resulting in a size reduction of up to 55% [17]. Also, multilayered topologies[18], meander lines[19], and multisection branch line couplers [20] can be used. Other examples include the use of short, high impedance transmission with shunt lumped capacitors and lines; two-step stubs with high and low impedance; stub lines with stepped impedance; synthetic transmission lines; capacitors distributed inside the area of the branch-line coupler; and microstrip lines with discontinuities in the branch-line hybrid coupler [21][22]. A size reduction of the branch-line coupler by 55.2%, with a fractional bandwidth of 56%, has been achieved using the combined lumped element technique and fractal geometry[23]. Another technique used to reduce the size of the planar circuit of a 3-dB branch-line coupler is by using cross slots, as suggested in [24].

This paper aims to review the various designs of conventional and hybrid branch-line couplers available in literature and address the two main design challenges: size miniaturization and bandwidth widening. The rest of the paper is organized as depicted in Figure1. This paper is divided into five sections. Section 2 presents a brief history of hybrid couplers, and discusses components of hybrid coupler, their design issues, and challenges. Section 3 discusses the types of hybrid coupler by classifying them by topology, and by phase shift. In Section 4, various wideband hybrid
couplers are presented along with techniques to reduce its size and enhance their bandwidth. Section 5 then presents the future directions, issues, and challenges for hybrid coupler prior to the conclusion in the final section.

2. COMPONENTS OF HYBRID COUPLERS

The first coupler was implemented in the form of a pair of capacitive probes separated at quarter-wavelength. This device, named the Bethe-hole coupler, was patented as U.S. Patent 2562281, and later published in a proceeding entitled “Directional Couplers” in 1944 [25]. In 1954, a directional coupler was presented by Bernard M. Oliver in a proceeding entitled “Directional Electromagnetic Couplers”[26]. In 1965, a theory on transmission line (TL) couplers in transverse electromagnetic (TEM) mode was written by Young and Cristal. The bandwidth improvement of directional couplers was mainly done by cascading an odd number of multiple transmission line sections [27]. Since then, researchers have made progress in innovative coupler implementations, with a focus on improving coupler parameters and structures[28], such as wideband enhancement for a 90° hybrid coupler through a phase inverter technique, as shown in Figure 2 [29]. Since a large circuit area leads to an increase in the cost of production, a modified coupler with a shortened coupled line in the middle branch has been proposed in [30]. The two sections are used to produce a wideband coupler with a fractional bandwidth of 55 %, but the circuit size is doubled compared to the conventional branch line coupler. A wideband operation was obtained by using electrically switchable components to result in satisfactory performance in [31]. Its compactness and cost efficiency, with adjustable output phase difference and equal power division makes this design suitable for implementation in beamforming networks and phased array antennas. Several variations of branch line couplers include the coupled-line couplers [32], waveguide couplers [33], and wideband coupler with ports extension [34].

3. TYPES OF HYBRID COUPLERS

3.1 CLASSIFICATION BY TOPOLOGY

3.1.1 BRANCH-LINE COUPLER

The branch-line coupler is widely known as the quarter-wavelength hybrid, as the signal received at the through and the coupled ports are 90° out-of-phase. It is one of the components used to implement Butler matrices. They are designed using directly connected circuit elements and are usually implemented by using either a distributed circuit element approach or by equivalent lumped elements [35]. Figure 3 shows the geometry of the conventional hybrid branch-line coupler.
The characteristic impedance of the mainline and shunt branches of a branch-line coupler can be expressed as follows [37].

\[ Z_{02} = Z_0 \sqrt{1 - |S_{31}|^2} \]  

(1)

\[ Z_{0p} = \frac{Z_0}{\sqrt{1 - |S_{21}|^2}} \]  

(2)

where \( Z_{02} \) and \( Z_{0p} \) are the characteristic impedances of the mainline and shunt branch line of any branch-line couplers. Several modifications have been proposed in literature for the conventional hybrid coupler shown in Figure 3, for example. This modified coupler design includes the comb-line hybrid coupler as shown in Figure 4 [38].

### 3.1.2 RING HYBRID COUPLER

A hybrid ring consists of four ports with three 90° and one 270° transmission lines[39]. It operates with a 180° phase shift between the output ports when the operating input port is in a common mode. The power division is enabled for two corresponding transmission lines by terminating the ports using the same impedance, whereas the other two lines must have the same characteristic impedances for the electrical length difference of 180° [40]. On the other hand, a coupled line ring hybrid (CRH) can be used for arbitrary power division ratio. Each of such hybrids have three single transmission line sections and a set of coupled transmission sections. Two identical capacitances can be optionally introduced on the coupled transmission section, and the overall structure features most of the properties of traditional ring hybrid, as shown in Figure 5 for the general coupled line ring hybrid (GCRH) [41]. Meanwhile, a four-port passive component that provide ultra-wideband (UWB) filtering function and 0°-180° hybrid coupling at the same time was proposed in [42]. The performance of the ring hybrid coupler SIW with electromagnetic band gap(EBG) was confirmed experimentally with a coupling factor of 3.79 dB and 12.5% of bandwidth around 8 GHz and an isolation loss of above 20 dB. Finally, it should be noted that the proposed structure is suitable with the combination of waveguide techniques proposed in [43]. Bandwidth enhancement in the hybrid ring coupler is performed by using lumped elements in the vicinity of the transmission line. To enhance bandwidth and miniaturize the branch-line coupler, the 270° arm can be replaced by a 90° transmission line, as was reported in [44]. In summary, the input and output (isolation) port must be separated from the hybrid ring coupler using balanced resistance loads to enable a wider bandwidth in the branch-line coupler [45]. Table 1 compares the recent work reported in literature on ring hybrid couplers.
3.1.3 RAT-RACE HYBRID COUPLER

The rat-race hybrid coupler is a primary circuit component of the power divider in microwave balanced mixers. Future wireless communication systems require the miniaturization, multifunctionality, and strong harmonic suppression in these hybrid couplers. Bandwidth enhancement considered is a key feature in designing design rat-race couplers. When the operating frequency is low, the dispersion factor increases the size of the circuit. Although the area of the circle can be reduced by using lumped elements to reduce the length of the transmission line, the inductance is usually low [51][52]. In the conventional rat-race hybrid coupler presented in [53], the ring structure adopted to power split resulted in a bandwidth of about 18%, as shown in Figure 6. It consists of four ports placed around one half of a ring resonator at angles of 0°, 60°, 120°, and 180°, with an inter-port distance of the operating frequency of $k_0 = 4$, as suggested in [54].

When each 90° transmission line section of a traditional ring hybrid is replaced with asymmetric T-type lines, the characteristic of the conventional ring hybrid at the operating frequencies will be maintained[55]. Another novel broadband rat-race coupler uses a phase inverter element at one of the ring arms[56]. The use of parallel-coupled lines is also capable of size reduction and harmonic suppression. A properly combined parallel-coupled line with an open stub will enable low pass filter characteristics and a quarter wavelength ($\lambda/4$) equivalent electrical length [57]. The most important factor to enable effective bandwidth enhancement is to maintain the phase relationship between the four branches of the rat-race coupler, independent of the frequency, as show in Figure 16 circuit configuration 180° for Rat-race and waveguide hybrid coupler [58]. Table 2 summarizes several main techniques used to reduce the size of the rat-race coupler.

3.1.4 WILKINSON POWER DIVIDER

The Wilkinson power divider is a component for RF power combination or power division between the output [67]. Invented in 1960 the circuit of the power divider can consist of 3 ports [68], or have four ports such as ring, rat-race hybrid coupler [69]. Alternatively, the circuit can be of the Gysel-type [70], with arbitrary power-splitting[71]-[72], as shown in Figure 8. Wilkinson power dividers supply the input phase power division and perform the combination of the input/output resistance matching with an additional feature of high isolation between the two output ports. To decrease the area for its implementation, power dividers based on quarter-wavelength transmission lines have been introduced in [73],[74]. The major issues with the conventional Wilkinson power divider include poor selectivity, and an increase in the circuit size leading an increase in integration complexity with other circuits[75]. A traditional Wilkinson power divider consists of $N$ quarter-wavelength transmission lines and isolation resistors. The isolation resistors between output ports allow isolation and impedance matching at output ports. Small-sized chip resistors are generally chosen to minimize parasitic effects; this requires very close placement of output ports. This fact indicates that additional lines are needed for physical output port separation,
which then increases the circuit size and the power loss [76]. This power divider consists of a substitute for each $\lambda/4$ section of the traditional Wilkinson power divider, as shown in Figure 9 [77]. A summary of the physical and electrical parameters of the Wilkinson power dividers available in literature is presented in Table 3.

### 3.1.5 T-JUNCTION

The T-junction is typically used in applications such as feeding networks, high power amplifiers, and mixers [86],[87]. The use of T-Junctions in these applications require the facilitation of power division with a high-power split. However, due to the constraints of the characteristic impedance of transmission lines, power division of greater than 10 dB is very difficult to achieve. To overcome this limitation, high impedance in transmission lines can be usually increased using chip-inductors [88],[89][90]. A general T-junction is shown in Figure 10, where $Y_o$ is the admittance of the port which is connected with two other ports, ports 2 and 3. These ports exist on both ends of the structure and do not require any specific termination resistance. The characteristic impedance and electrical length of the transmission line between port 1 and port 2 are $Y_a$ and $\Theta_a$, respectively, whereas the same characteristic impedance and electrical length between port 1 and port 3 are $Y_b$ and $\Theta_b$. The relation between the currents and voltages of the two-transmission line are as follows [91]:

\[
\begin{bmatrix}
I_2 \\
I_1a
\end{bmatrix} =
\begin{bmatrix}
Y_{11a} & Y_{12a} \\
Y_{21a} & Y_{22a}
\end{bmatrix}
\begin{bmatrix}
V_2 \\
V_1
\end{bmatrix}
\]

(3a)

$$I_{1a} + I_{1b} + I_{11} = I_{1a} + I_{1b} + Y_0V_1 = 0$$

(3b)

Where the current $I_1$ in port 2, $I_3$ in port 3 and $I_{1a}$, $I_{1b}$ and $I_{11}$ in port 3 are indicated over along the identical voltage $V_1$, $V_2$, and $V_3$, and;

\[
\begin{bmatrix}
Y_{11a} & Y_{12a} \\
Y_{21a} & Y_{22a}
\end{bmatrix} =
\begin{bmatrix}
-jY_{acot\Theta a} & jY_{asc\Theta a} \\
-jY_{asc\Theta a} & jY_{acot\Theta a}
\end{bmatrix}
\]

(3c)

\[
\begin{bmatrix}
Y_{11b} & Y_{12b} \\
Y_{21b} & Y_{22b}
\end{bmatrix} =
\begin{bmatrix}
-jY_{bcost\Theta b} & jY_{basc\Theta b} \\
-jY_{basc\Theta b} & jY_{bcost\Theta b}
\end{bmatrix}
\]

(3d)

Substituting $I_{1a}$ and $I_{1b}$ in (3a) and (3b) into (3c)

$$Y_{21a}V_2 + Y_{22a}V_1 + Y_{11b}V_1 + Y_{12b}V_3 + V_1Y_0 = 0$$

(4)
From (4) \( V_1 \) can be derived as

\[
V_1 = \frac{Y_{21a}V_2 + Y_{12b}V_3}{Y_{11b} + Y_{22a} + Y_0}
\]  

(5)

Substituting \( V_1 \) (5) into \( I_2 \) and \( I_3 \) in (6a) and (6b) provides the relation between the currents \( I_2 \) and \( I_3 \) and the voltage \( V_2 \) and \( V_3 \).

\[
I_2 = Y_{11a}V_2 - Y_{12b}Y_{11b} + Y_{22a} + Y_0
\]  

(6a)

\[
I_3 = -Y_{21b}Y_{11b} + Y_{22a} + Y_0 + Y_{12b}V_3
\]  

(6b)

The admittance parameters of the in-phase T-junction can be derived from (6) as:

\[
Y_{11} = Y_{11a} - \frac{Y_{12b}Y_{21a}}{Y_{11b} + Y_{22a} + Y_0}
\]  

(7a)

\[
Y_{12} = Y_{21a} - \frac{Y_{12b}Y_{12b}}{Y_{11b} + Y_{22a} + Y_0}
\]  

(7b)

\[
Y_{22} = Y_{22b} - \frac{Y_{12b}Y_{21b}}{Y_{11b} + Y_{22a} + Y_0}
\]  

(7c)

Based on the expressions in (7), the acceptance parameters of the Gysel power divider in [92].

### 3.2 CLASSIFICATION BY PHASE-SHIFT

#### 3.2.1 90° HYBRID COUPLERS

The 3dB hybrid branch-line coupler with 90° phase shift is an important component for in-phase and quadrature (I/Q) signal generation with equal split power [93]. This structure is also widely used due to its simple design and ease of fabrication [94]. The design fundamentals of such couplers are explained in [95]. Different implementations have been proposed in literature based on its applications [96][97], which includes micromachining methods to reduce size [98]. Besides this, capacitive load have been implemented to achieve low resistance stubs [99], [100], or loading the structure using metamaterials, or by including structures with different impedance [101]. Moreover, the 3dB 90° hybrid coupler with equal power division is often applied in a circularly
polarized antennas [102], [103]. Finally, wideband 90° 3 dB directional branch-line coupler is also a key component to correlate a six-port circuit for wireless ultra-wideband (UWB) communication system [104]. Different techniques have been introduced to reduce loss in such hybrid couplers, such as SIW branch-line connectors in literature [105], [106]. Another technique for broadband directional coupler uses asymmetric waveguide based phase control on the silicon-nonconductor platform, as shown in Figure 11 [107]. The 3dB 90° hybrid coupler can also be customized further by placing a 45° phase shifter, resulting in the achievement of 45° or 135° of phase shift variations. In comparison to asymmetric phase shifter with phase variants and equal length, designs of hybrid couplers with unequal width provides better phase properties [108]. Conventional designs of hybrid couplers with 90° of phase shift typically produce about 10% of bandwidth [109]. The conventional method to improve bandwidth include the design of multiple sections of coupler in series. However, such technique results in a large structure due to the required transmission lines with high characteristics impedance in the coupler. This lowers space efficiency [110], [111]. Wideband branch-line coupler using coupled line has a good bandwidth performance, but it is hard to design and implement [112]. Another way to increase the bandwidth of the coupler is by using a multi-chain coupling slot, as shown in Figure 12. The hybrid branch-line couplers are assumed to have fixed input power to the feeding waveguide through all of the small amounts of coupling at the holes [113].

3.2.2 180° HYBRID COUPLERS

The 180° hybrid branch-line coupler is a standard for the microwave component which divides a signal into phase (Σ) and out of phase (Δ) components [114]. Hybrid branch-line coupler can be applied in mixers, antenna feeds and beamforming networks [115]. It is a four-port network device that realizes multilateral power combining/dividing operation, separating the sum and the difference of two input signals [116]. Other variations of hybrid branch-line couplers include the types which provide 3 dB 90° and 180° output signals [117]. Conventional hybrid branch-line coupler can be implemented using different techniques [118]. An example is the hybrid branch-line coupler and directional coupler for 180° used in the receiver of the Sardinia Radio Telescope (SRT) [119]. It operates between 300 MHz and 410 MHz (31% relative bandwidth). Many different researchers have focused on improving various aspects in this hybrid branch line coupler. They include the issue of achieving out-of-phase power split to maintain a perfectly identical port [59], [120]; spurious signal repression [121], [122]; broadband operation [123], [124]; dual-band operation [125], [126] and arbitrary power division [127], [128]. Besides 90° hybrid branch-line couplers, different design procedures have been proposed for the 180° hybrid branch-line couplers in [129]. This structure is designed based on the 90° and 180° coupling lines which can provide 180° hybrid coupling in both frequency bands [130]. The design of a 180° hybrid wideband coupler utilizing two substrate layers, slotted ground and a microstrip lines for all four ports is shown in Figure 13 [131]. The 180° hybrid branch-line coupler can be miniaturized by folding the shared couple line between the input of the power divider and output, as proposed in [132].
couple line require an equal length at both port ends. An example of such hybrid branch-line coupler proposed in [133], as shown in Figure 14.

4. WIDEBAND HYBRID COUPLERS

This section explains the designs of wideband hybrid coupler based on recent previous studies. This includes a new design of the wideband and compact branch-line coupler by using integrated passive device (IPD) technique operating at the frequency of 60 GHz suggested by [134]. Next, another wideband and compact 180° branch-line coupler, composed of symmetrical four \( \lambda/4 \) strips interdigitated coupler is proposed in [135]. This resulted in a wide 60% bandwidth of operation with a compact size. Meanwhile, the design of compact branch-line coupler can also be achieved by using a T-shaped transmission line connected with a parallel open stub. The use of the T-shaped and open stub enabled miniaturization and harmonic suppression of up to 74% in [136]. Besides that, the use of a three parallel-coupled line couplers design, based on the even and odd modes, can be used to improve bandwidth due to the higher coupling factor compared to the conventional two-line parallel coupled design [30]. Another new design method to obtain wider bandwidth is by substituting cascaded slow-wave cells in place of the conventional transmission line, as demonstrated by the compact coupler in [137]. A wideband coupler with compact size, low loss, and low-cost reconfigurable transmission lines was introduced in [31]. This work also includes the electrical-switchable equivalent characteristic impedance and length of the proposed design. Meanwhile, the design of a three-section wideband hybrid branch-line coupler with harmonic suppression using a new transmission line model has been reported in [20]. Besides that, the substrate-integrated-waveguide (SIW) technology can be used to design a hybrid coupler. A power divider, a 90° phase shifter, and a 90° bend, provides improved bandwidth performance from 35 GHz to 47 GHz in [138]. Next, a 90° directional coupler design using a very low capacitance imbalance is designed in [139]. The primary characteristic of this coupler is to provide a controllable ripple in the operating range to improve the overall amplitude balance. The control of ripples in the operating range improved the overall defects in capacitance, whereas conductive patches and slits are used to control the coupling phase and bandwidth [140]. Meanwhile, a hybrid branch-line coupler consists of four sections of equal lengths of the transmission line sections with two distinct and different identical L-sections and open arms is proposed in [141]. To achieve a wide bandwidth for the 90° hybrid 3-dB coupler, the lumped element technique was used [142]. Figure 15 illustrates the different designs and techniques used to design wideband hybrid branch-line coupler, whereas Figure 16 illustrates the properties of the reconfigurable coupler [31] including S-parameters amplitude, coupling between ports and phase error difference. Table 4 summarizes and qualitatively compares various technologies available to enable the wideband operation of hybrid couplers.

5. OPEN PROBLEMS AND FUTURE DIRECTIONS

The key issues and challenges in the design of convention hybrid couplers are their bulky size and narrow bandwidth. Size, cost, losses, and bandwidth are often the biggest limitations in their implementation. Keeping these limitations in mind, researchers must provide a diverse set of
designs to satisfy different frequency bands. Noting the overwhelmingly large spectrum of communication systems, it would be ideal for manufacturers to provide a solution which satisfies needs over a significant range of these frequencies. A case in which this issue is clearly seen is in mobile phone applications. Current solutions available for mobile phone applications currently provide bandwidths between 7 % and 20 % [15]. These bandwidths are relatively limited and implementing the same device in other applications with different center frequencies would prove to be non-functional. It is important to note that 90° hybrid couplers are tuned to specific frequencies, and this will be the case even with any improved design. However, if significant bandwidth improvement can be achieved by these devices, it would prove to be advantageous, reducing costs while increasing device efficiency. Various methods to improve the bandwidth and achieve size reduction are proposed in [21][22][23]. The main goal is to have one device broad enough to satisfy a wide range of frequency applications.

6. CONCLUSION

The hybrid coupler is one of the most important components in wireless communication systems for the division and combination of the power. This article introduces an in-depth overview of the state-of-the-art research on the hybrid couplers, which is mainly used to either divide an input signal with a phase shift between two outputs ports, or used to combine two incoming signals. This is ideally done while maintaining a high isolation between the two ports. Besides that, this review has provided an exhaustive summary of various techniques used in improving the size and bandwidth of couplers, which are the two major design challenges. These techniques include the T-shaped meander line, slotted microstrip line, multi (two- or three-) section lines, and parallel-coupled lines. Finally, the last two sections have been dedicated to review the ring hybrid and rat race hybrid couplers and present their emerging design issues and challenges. This leads to the design aspect of low-cost Butler matrices, an important component in future wireless communication technologies.

REFERENCES


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Dear Editor-in-Chief, Associate Editor,

We would like to sincerely express our appreciation to you and the reviewers for their valuable comments and remarks. This has resulted in the manuscript's significant improvement. Every comment/remark has been taken into careful consideration, and our response to each is explained as follows.

Reviewer(s)' Comments to Author:

Reviewer 1

This review paper does not provide novel ideas or suggestions for future design of couplers.
This paper is just simply combing some published papers.

We are thankful to the reviewer for pointing out this shortcoming. We have completely re-organized the paper and added a new section on open problems and future directions to better summarize the essence of this review.

Reviewer 2

1 - undefined acronym "BLC".

We thanks this reviewer and apologize for this. In the revised manuscript, we have used the name in full, i.e. branch-line coupler throughout.

Reviewer 2

Reviewer(s)' Comments to Author:

2- please insert the reference of the Table 1 into the text.

Thank you for pointing this out. Table 1 (now Table 3 in the revised manuscript) is now cited in the text (Section 3.1.4, last line), as follows: “A summary of the physical and electrical parameters of the Wilkinson power dividers available in literature is presented in Table 3”.

3. The formulas 3a and 3b are the same.

We thank the reviewer for pointing out this error. We have corrected the formulas in this revision.

4. check the use of subscript in formulas between 3c and 6b
We have revised the use of subscripts in the formulas between 3c and 6b.

5. The figure 8 doesn't show "the different properties of couplers", but the properties of a specific reconfigurable coupler.

We thank the reviewer for pointing this out. We have revised the caption of the figure (now Figure 16) to properly reflect that it illustrates the properties of a specific reconfigurable coupler including S-parameters amplitude, coupling between ports and phase error difference.

6. To improve the caption of Figure 8 by providing additional information about the coupler.

The caption of Figure 8 (now Figure 16 in the revised manuscript) has been changed as follows:

Figure16. Different parameters analysis for coupler shown in (a) and (c). (a) S-parameters of coupler a = 15°. (b) The phase difference of coupler a = 15°. (c) S-parameters of coupler a = 30°. (d) The phase difference of coupler a = 30°[31].

7. undefined acronym "UWB."

In this revision, we have defined the acronym UWB as ultra-wideband.

8. undefined acronym "EBG"

In this revision, we have defined the acronym EBG as electromagnetic band gap.

9. please to correct the reference "Hybrid-Ring Arbitrary" with "Hybrid-Ring Directional Coupler for Arbitrary Power Divisions".

We are grateful to the reviewer for pointing this out. The reference has been corrected as shown below:

Figure 1: Skeletal structure of this review
Figure 2. (a) Geometry of a parallel-strip phase inverter with metal conductors only. (b) Top view of the parallel-strip phase inverter (c) Top view of the phase inverter with two sections of parallel-strip lines.
Figure 3. Conventional design of the hybrid branch-line coupler [36].
Figure 4: (a) Conventional hybrid coupler, and (b) comb-line hybrid coupler
Figure 5. General coupled-line ring hybrid (GCRH) for arbitrary circumferences
Figure 6. The geometry of the rat-race coupler
Figure 7. Circuit configuration of a 180° hybrid coupler: (a) Rat-race coupler, (b) tapered coupler, and (c) magic-T hybrid coupler
Figure 8. Power divider filtering Gysel with arbitrary ratios.
Figure 9. The conventional Wilkinson power divider.
Figure 10. Section view of the T-junction [91].
Figure 11: Schematic of the broadband hybrid branch-line coupler[107]
Figure 12. The geometry of the six-stage 90° hybrid coupler [113].
Figure 13. 180° hybrid coupler with slotted ground beside the microstrip lines [131]
Figure 14. The layout of the 180° hybrid coupler [133]
Figure 15. Block diagram for a hybrid coupler (a) 3 dB quadrature hybrid coupler [143]. (b) Hybrid branch-line coupler [141]. (c) Hybrid branch-line coupler with substrate integrated gap waveguide (SIGW) [144].
Figure 16. Different parameters for the coupler shown in Figure 15(a) and (c). (a) S-parameters of coupler with \( a = 15^\circ \). (b) The phase difference of coupler with \( a = 15^\circ \). (c) S-parameters of coupler with \( a = 30^\circ \). (d) The phase difference of coupler with \( a = 30^\circ \)[31].
<table>
<thead>
<tr>
<th>Ref</th>
<th>Freq (GHz)</th>
<th>Power ratio (dB)</th>
<th>Power ratio variation (dB)</th>
<th>BWD (%)</th>
<th>S11 (dB)</th>
<th>S41 (dB)</th>
<th>Physical size (λₚ×λₛ)</th>
<th>Impedance transformation</th>
<th>Configuration</th>
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<td>[40]</td>
<td>1</td>
<td>12 dB</td>
<td>&lt;1dB</td>
<td>78</td>
<td>-15</td>
<td>-30</td>
<td>0.33 × 0.37</td>
<td>no</td>
<td>Wilkinson power divider (WPD)</td>
</tr>
<tr>
<td>[46]</td>
<td>2</td>
<td>10 dB</td>
<td>&lt;1dB</td>
<td>100</td>
<td>-20</td>
<td>-30</td>
<td>0.84 × 0.92</td>
<td>yes</td>
<td>Ring structure</td>
</tr>
<tr>
<td>[47]</td>
<td>2</td>
<td>20 dB</td>
<td>&gt;1dB</td>
<td>85.5</td>
<td>-15</td>
<td>-25</td>
<td>0.45 × 0.36</td>
<td>no</td>
<td>Ring structure and 3D- structure</td>
</tr>
<tr>
<td>[48]</td>
<td>2</td>
<td>10.8 dB</td>
<td>&lt;1dB</td>
<td>100</td>
<td>-15</td>
<td>-22</td>
<td>0.41 × 0.66</td>
<td>no</td>
<td>Ring structure</td>
</tr>
<tr>
<td>[49]</td>
<td>2</td>
<td>10 dB</td>
<td>&lt;1dB</td>
<td>17</td>
<td>-10</td>
<td>-20</td>
<td>0.80 × 0.45</td>
<td>no</td>
<td>Wilkinson power divider</td>
</tr>
<tr>
<td>[50]</td>
<td>1.4</td>
<td>11.76 dB</td>
<td>&lt;1dB</td>
<td>14.8</td>
<td>-20</td>
<td>-34</td>
<td>0.64 × 0.38</td>
<td>no</td>
<td>Ring structure</td>
</tr>
</tbody>
</table>
Table 2. Summary of literature focusing on the size reduction of rat-race couplers.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Frequency (GHz)</th>
<th>S11 (dB)</th>
<th>Relative area reduction</th>
<th>Isolation (dB)</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>[59]</td>
<td>0.9</td>
<td>-20</td>
<td>50.7%</td>
<td>-20</td>
<td>Low impedance section</td>
</tr>
<tr>
<td>[60]</td>
<td>0.9</td>
<td>-10</td>
<td>3.9%</td>
<td>-10</td>
<td>Shunt-stub-based transmission line</td>
</tr>
<tr>
<td>[61]</td>
<td>1.8</td>
<td>-23</td>
<td>30%</td>
<td>-20</td>
<td>Meander-curves</td>
</tr>
<tr>
<td>[62]</td>
<td>2.4</td>
<td>-20</td>
<td>15.4% and 12.6%</td>
<td>-20</td>
<td>Sierpinski and shaped rat-race coupler</td>
</tr>
<tr>
<td>[63]</td>
<td>2</td>
<td>Not reported</td>
<td>15%</td>
<td>Not reported</td>
<td>The rat-race coupler and photonic band-gap cells</td>
</tr>
<tr>
<td>[64]</td>
<td>1.44</td>
<td>-15</td>
<td>8%</td>
<td>-20</td>
<td>High and low impedance resonant cells</td>
</tr>
<tr>
<td>[65]</td>
<td>1.2</td>
<td>-20</td>
<td>18.5%</td>
<td>-20</td>
<td>Fractals</td>
</tr>
<tr>
<td>[66]</td>
<td>1</td>
<td>-20</td>
<td>25%</td>
<td>-20</td>
<td>Multiple-open stubs</td>
</tr>
</tbody>
</table>
Table 3. Comparison between the physical and electrical parameters of the Wilkinson power dividers available in literature.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Technique applied</th>
<th>$f_2/f_1$</th>
<th>$k^2$</th>
<th>Input, Output matching (dB)</th>
<th>Isolation (dB)</th>
<th>Size (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[78]</td>
<td>Single/Multi- T section configurations</td>
<td>2:00</td>
<td>10</td>
<td>-20, -18</td>
<td>-25</td>
<td>82 × 160</td>
</tr>
<tr>
<td>[79]</td>
<td>Coupled line with short stubs</td>
<td>1.80</td>
<td>7</td>
<td>-20, -20</td>
<td>-20</td>
<td>95 × 105</td>
</tr>
<tr>
<td>[80]</td>
<td>Lumped RLC components</td>
<td>2.50</td>
<td>2</td>
<td>-20, -25</td>
<td>-20</td>
<td>63 × 230</td>
</tr>
<tr>
<td>[81]</td>
<td>Multi- section from transmission lines</td>
<td>2.68</td>
<td>2</td>
<td>-25, -30</td>
<td>-30</td>
<td>60 × 94</td>
</tr>
<tr>
<td>[82]</td>
<td>Single T-section with short/open stubs</td>
<td>1.8</td>
<td>2</td>
<td>-40, -25</td>
<td>-30</td>
<td>88 × 130</td>
</tr>
<tr>
<td>[83]</td>
<td>Π-section the input/output ports</td>
<td>2:00</td>
<td>2</td>
<td>-20, -20</td>
<td>-30</td>
<td>53 × 106</td>
</tr>
<tr>
<td>[84]</td>
<td>Lumped RLC components</td>
<td>4:00</td>
<td>2</td>
<td>-30, -30</td>
<td>-30</td>
<td>65 × 240</td>
</tr>
<tr>
<td>[85]</td>
<td>Multi- section coupled transmission lines</td>
<td>2.50</td>
<td>2</td>
<td>-25, -20</td>
<td>-40</td>
<td>64 × 90</td>
</tr>
</tbody>
</table>
Table 4. Comparison of wideband hybrid couplers available in literature.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Technology</th>
<th>Material</th>
<th>Dim (mm²)</th>
<th>TL (mm)</th>
<th>BW (%)</th>
<th>Isolation (dB)</th>
<th>Phase imbalance</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[30]</td>
<td>Shorted coupled three-line</td>
<td>Taconic CER-10</td>
<td>15 × 15.9</td>
<td>29.4 × 15.9</td>
<td>55</td>
<td>20.8</td>
<td>±3.2°</td>
<td>1.9</td>
</tr>
<tr>
<td>[31]</td>
<td>Electrically switchable</td>
<td>RT/Duroid 5880</td>
<td>90×60</td>
<td>Not reported</td>
<td>30</td>
<td>4</td>
<td>90° and 90 ± a°</td>
<td>2.4</td>
</tr>
<tr>
<td>[134]</td>
<td>Integrated passive device (IPD)</td>
<td>Glass</td>
<td>563 ×574</td>
<td>3.0</td>
<td>57–66</td>
<td>10</td>
<td>±5°</td>
<td>60</td>
</tr>
<tr>
<td>[135]</td>
<td>Symmetrical four-strip interdigitated coupler</td>
<td>Taconic RF-35</td>
<td>48.3 ×42.8</td>
<td>1.78</td>
<td>62</td>
<td>30</td>
<td>±2°</td>
<td>1.26</td>
</tr>
<tr>
<td>[136]</td>
<td>Transmission line connected with T-shaped and parallel open stubs</td>
<td>STSTL on RT duroid</td>
<td>74× 63</td>
<td>39.6°/37.8°</td>
<td>20</td>
<td>20</td>
<td>90 ± 5°</td>
<td>0.9</td>
</tr>
<tr>
<td>[137]</td>
<td>Cascaded slow-wave cells in conventional transmission lines.</td>
<td>Taconic RF-35</td>
<td>46.58×33.9</td>
<td>2</td>
<td>51.6 × 36.6</td>
<td>32</td>
<td>~90°</td>
<td>1</td>
</tr>
<tr>
<td>[139]</td>
<td>Microstrip transmission lines</td>
<td>Alumina</td>
<td>3λ/4 ×λ/4</td>
<td>Not reported</td>
<td>65</td>
<td>12</td>
<td>90 ±8.5°</td>
<td>4–7.9</td>
</tr>
<tr>
<td>[145]</td>
<td>A substrate integrated waveguide ring coupler and a half-mode</td>
<td>Name not specified. $\varepsilon_r = 2.2$ and $\tan\delta = 0.001$</td>
<td>53 × 45</td>
<td>30.8</td>
<td>24.6</td>
<td>10</td>
<td>15.0° ~ 5.8 and 175.5° ~ 189.7°</td>
<td>10.2</td>
</tr>
<tr>
<td>[146]</td>
<td>Three channels in the multiplexer</td>
<td>aluminum</td>
<td>20 ×20 × 20</td>
<td>Not reported</td>
<td>25</td>
<td>Not reported</td>
<td>−15.1</td>
<td>40</td>
</tr>
<tr>
<td>[147]</td>
<td>MS gap between two differential transmission lines</td>
<td>RO4725JXR</td>
<td>1.32 × 1.32</td>
<td>150</td>
<td>30</td>
<td>Not reported</td>
<td>180 ± 5°</td>
<td>2.27–3.07</td>
</tr>
</tbody>
</table>