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Development of Compact and Flexible Quadrature Hybrid Coupler Using Coaxial Cable with Capacitive Loading for 1.5 T Indigenous MRI System

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Abstract—Quadrature feeding is essential in magnetic resonance imaging radio frequency (MRI-RF) coils, to improve the homogeneity of the magnetic field of surface coil, the signal to noise ratio (SNR) of the image by a factor of $\sqrt{2}$, and to create a circularly polarized magnetic field inside the volume coil. The quadrature feeding is incorporated, using hybrid coupler. However, at 63.87 MHz the Larmor frequency of hydrogen proton, corresponding to 1.5 Tesla, the size of the hybrid coupler and other microwave circuits become large. So, to minimize its physical size, a coaxial cable transmission line with lumped capacitive loading has been proposed. The size of the proposed hybrid coupler is reduced by 68%, as compared to the conventional hybrid coupler. The proposed device is then fabricated as a both rigid and flexible structure, which provides isolation (S_{41}) of around 19 dB and a 90° phase difference between coupled and the through ports. Both structures provide return loss $S_{11} > -15$ dB and coupling at output ports S_{21}, S_{31} around 3 dB.

1. INTRODUCTION

In MRI, coil is an essential element that transmits and receives B1 magnetic field. There are mainly two types of coils in MRI. One is surface coil, and the other is volume coil. Surface coils are designed as per different body parts, and they are always in a state of receiving mode. Volume coils such as Body-Birdcage coil and Head coil are designed to provide homogeneous and circularly polarized field, but they work in both transmitting and receiving mode [1]. Volume coil and Quadrature surface coils require In-phase, and Quadrature phase feeding for achieving three primary objectives, namely, generating a circularly polarized B1 magnetic field, improving the homogeneity of the magnetic field [2], and increasing the SNR of the image by a factor of $\sqrt{2}$ [3]. Hence, there is a need to drive both the coils by a 3 dB Hybrid Coupler. Hybrid coupler, also known as branch-line coupler, consists of two quarter-wave transmission line sections with a characteristic impedance value of Z_0 along the vertical arm and $Z_0/\sqrt{2}$ along the horizontal arm [4]. Apart from MRI, hybrid couplers are used in several other applications like Circular Polarized Antenna, Power Divider/Combiner, Shifter, etc. They also serve as an impedance matching device between the input and output ports. At 1.5 T, the Larmor frequency for hydrogen proton is 63.87 MHz, and the corresponding wavelength is 4.7 m [5]. As per the conventional design, a 3 dB hybrid coupler at the Larmor frequency would have dimensions of 1.17 m in both arms, which are too large and impractical to use in MRI system. Therefore, miniaturization becomes a prerequisite. The available options for miniaturization of the traditional hybrid coupler are the use of the lumped element, microstrip line, stripline, coaxial cable, and waveguide. At high power (10 kW–35 kW, which is generally required to feed energy to body coil [6]), the lumped element hybrid

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coupler becomes very bulky and costly. Microstrip based hybrid couplers have a limited power handling capacity [7]. Waveguides can handle high power, but they are mostly suitable in the microwave range, and their miniaturization is also difficult at lower radio frequency. An attempt was made using stripline technique by Crnadak and Tasić [8], in which a broadside coupled stripline coupler in VHF band is presented for frequency 175 MHz using brass conductor and air as a homogenous medium. The design was improved by introducing hetero junction medium of Teflon and air [9]. The same design is further modified by a crossed strip which results in compactness in its dimension [10]. In all above designs [8–10], the authors claimed for power handling capacity of around 32 kW, but there is no comment on its losses due to thick metal strip. Due to these limitations, the coaxial based approach appears as the best match for our application. The only problem with this approach is that it requires two coaxial cables with characteristic impedances of 50 Ω and 35 Ω, respectively. In [11], a 3 dB Rat Race Hybrid Coupler (RRHC) was realized using coaxial cable at frequency 260 MHz. The authors claimed a 96.6% reduction in size, but this was done by rounding the flexible coaxial cable and not by reduction in its physical length. In the last few years, many methods have been proposed to reduce the overall size of microwave devices like capacitive loading to minimize the size of Wilkinson Power Divider [12, 13] abd inductively loaded microstrip line for harmonic suppression [14]. In another approach, distributed capacitors were placed in the empty spaces available in the hybrid coupler which greatly reduced the size compared with conventional coupler [15, 16]. With considering above limitations, we decided to go for coaxial based approach and to reduce its physical length, and we used capacitive loading technique.

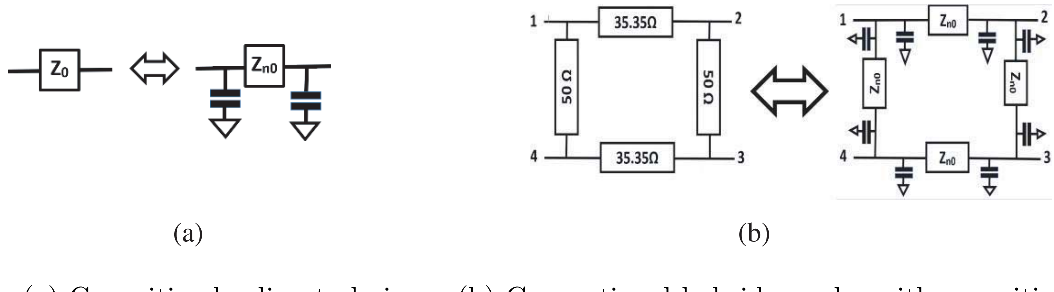
In this paper, the design and fabrication of a compact 3 dB branch-line coupler, using capacitive loading, is proposed with size reduction of 68% compared to conventional hybrid coupler. The most exciting feature of the proposed coupler is that it can handle high power, due to the use of a coaxial cable. The whole assembly is developed on an Arlon 320 substrate sheet. The proposed design is made flexible, by removing the extra substrate area. The proposed structure is designed, using advanced design system (ADS) and Matrix laboratory (MATLAB) simulation software.

2. LENGTH REDUCTION PRINCIPLE

There are two ways by which the length of a transmission line can be reduced. One is inductive loading, and the other is capacitive loading. If a transmission line is terminated at each port by an inductor in series, then it is known as inductive loading, and when it is terminated at each port by a capacitor in parallel, then it is known as capacitive loading.

Principle: *When the length of a transmission line is reduced, its equivalent inductance and capacitance, both, get reduced. So, to compensate reduced capacitance, the characteristic impedance of a new transmission line increases in the case of capacitive loading and decreases in the case of inductive loading. Similarly, to compensate reduced inductance, we have to add inductor in series for inductive loading and capacitor in parallel in the case of capacitive loading.*

For our design, a capacitive loading technique is used which is depicted in Fig. 1(a). However, one can use any loading technique, depending on availability of resources and size requirement. It is advisable to fix characteristic impedance of a transmission line first (here 75 Ω) and then calculate the length of a new transmission line from formulae mentioned in design section.



(a) (b)

Figure 1. (a) Capacitive loading technique. (b) Conventional hybrid coupler with capacitive loading.

3. DESIGN THEORY OF HYBRID COUPLER

Both vertical ($Z_0 = 50\,\Omega$) and horizontal ($Z_0 = 35.35\,\Omega$) arms of the hybrid coupler are equated with coaxial cable ($Z_{n0} = 75\,\Omega$), which is loaded with a capacitor. The length of the new transmission line and its capacitance value are obtained, from the analysis of $ABCD$ parameters of conventional and compact hybrid couplers [17]. It is observed that the characteristic impedance, length of line, and its corresponding capacitance are related as,

$$Z_{n0} = \frac{z_0}{\sin\beta \times L} \tag{1}$$

where,

Characteristic impedance of new compact coupler $Z_{n0} = 75\,\Omega$.

Characteristic impedance of vertical and horizontal arm $Z_0 = 50\,\Omega$ and $35.35\,\Omega$.

$L =$ length of the new compact hybrid couple.

$$\beta = \frac{2\pi\sqrt{\varepsilon_r}}{\lambda_0} \tag{2}$$

where,

$\varepsilon_r =$ Dielectric constant of coax cable having characteristic impedance Z_{n0}.

$\lambda_0 =$ Free space wavelength corresponding to frequency of operation (f) 63.87 MHz and Capacitance is given by

$$C = \frac{\cos\theta}{2z_0\pi f} \tag{3}$$

It shows that with Z_{n0} being $75\,\Omega$, the cable length is 37.5 cm for vertical arm (Z_0 being $50\,\Omega$) and 25 cm for horizontal arm (Z_0 being $35.35\,\Omega$). The capacitance value for the vertical arm is found to be 37.14 pF, and the horizontal arm is 62.86 pF. As both capacitors are in parallel (as shown in Fig. 1(b)), they can be added to miniaturize the circuit design. So, the final value of the capacitor for both arms is 100 pF. Instead of calculating capacitance for each arm, we can use the formula below to get the final value [18].

$$C = \frac{\sqrt{1 - \left(\frac{z_0}{z_{n0}}\right)^2} + \sqrt{2 - \left(\frac{z_0}{z_{n0}}\right)^2}}{2\pi f Z_0} \tag{4}$$

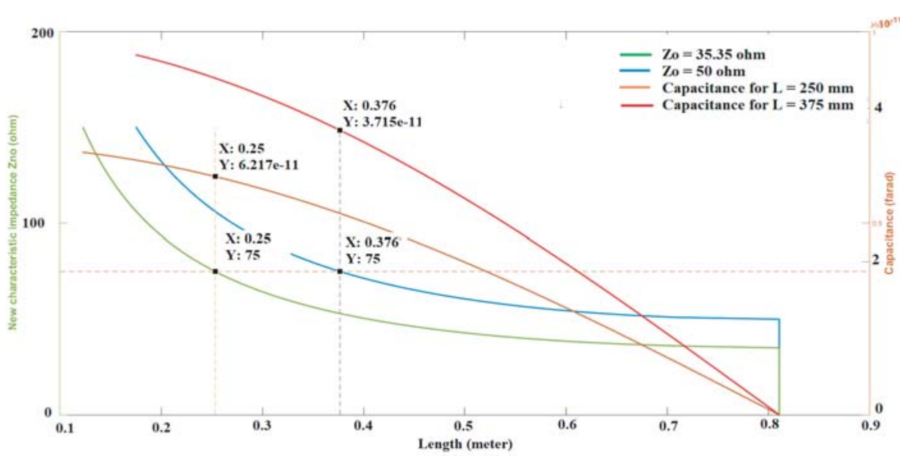


Figure 2. Variation of length and capacitance w.r.t. characteristic impedance Z_{n0}.

The above formula (Equation (4)) also results in the same value as calculated, using Equation (3) for both arms. A MATLAB code was written to study the variation of length and capacitance w.r.t. variation in characteristic impedance Z_{n0} from 0 to 200 Ω. This variation among length, capacitance, and new characteristic impedance is shown in Fig. 2.

The above graph (shown in Fig. 2) also results in same value that we got from mathematical analysis. The graph also indicates that as we take higher characteristic impedance cable, the size of hybrid coupler further decreases, but at the same time values of capacitors also increase.

4. SIMULATION OF DEVICE

The whole circuit is then simulated on ADS software, using the values obtained from theoretical calculations in design section. Fig. 3 represents the schematic of the circuit diagram of the compact hybrid coupler. The details of the coaxial cable are taken from datasheet [18], and the circuit is simulated for the same.

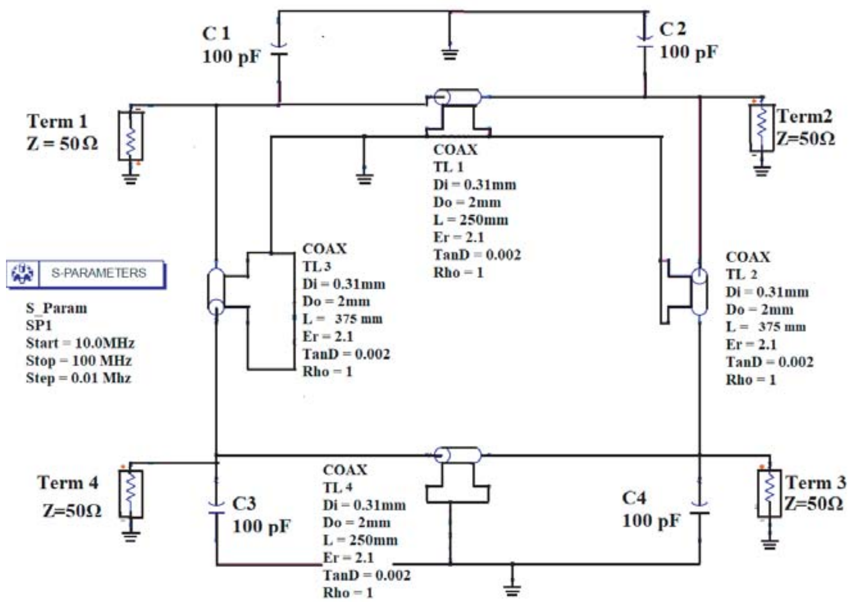


Figure 3. Simulated circuit model of the compact coupler in ADS software.

Simulated results are compared with measured ones (on Performance Network Analyzer — PNA) using Origin software for comparative plotting. Fig. 4 depicts the comparative analysis of S parameters for both simulated and measured results. S_{21} and S_{31} show the coupling between through and coupled ports, whereas S_{11} shows the reflection coefficient at the input port and S_{41} as the isolation between input and isolation ports. Measurements were also done on the phase difference between output ports and compared with simulated results.

5. FABRICATION AND MEASUREMENT RESULTS OF THE COMPACT HYBRID COUPLER

The circuit, after design and simulation, is then fabricated using coaxial cable RG187 [19] having a characteristic impedance of 75 Ω and a capacitance of value 100 pF with a 2–10 pF variable capacitor (Company: Knowles Electronics) for optimization. For mechanical support, the whole structure is developed on an Arlon 320 substrate having a thickness of 3.2 mm. The hybrid coupler prototype (Fig. 5(a)) is then tested on Agilent Technology PNA-N5221A. According to the RG187 datasheet, it is capable of handling a maximum of 1.4 kW of power [18]. In MRI, body coil requires around 16–20 kW

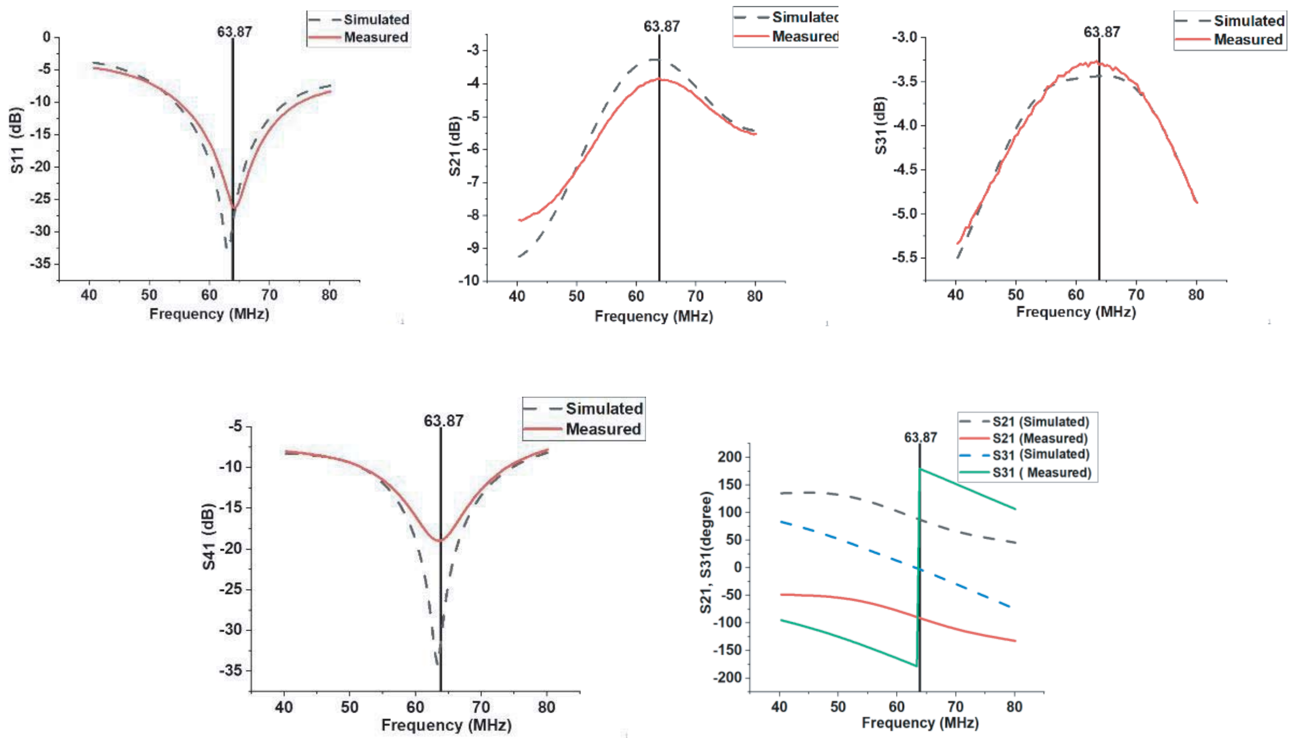
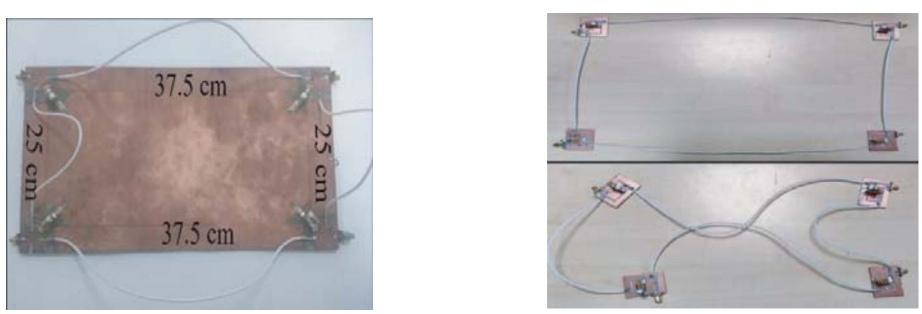


Figure 4. Simulated and measured of S and phase difference parameters of the flexible hybrid coupler.



(a) (b)

Figure 5. (a) Prototype of the compact hybrid coupler. (b) Flexible hybrid coupler.

of power for a full-body scan. So, to excite such high power, we have to replace RG187 coaxial cable with a suitable cable, whose power handling capacity is around 20–25 kW.

Simulated and measured data for the compact hybrid coupler are summarized in Table 1. The results are close to each other.

There is a mismatch between simulated and measured phase differences in S_{21} and S_{31} parameters. The absence of printed circuit board (PCB) during simulation in ADS or fabrication error leading to parasitic effect may result in the mismatch between the simulated and measured phase differences.

6. FABRICATION AND MEASUREMENT OF FLEXIBLE HYBRID COUPLER

For compact structure, we used an Arlon 320 substrate as mechanical support. However, to investigate its effects on the S parameter and to make the structure more flexible, we shifted the whole assembly of the hybrid coupler on a four small corner substrate of the same material Arlon 320. The length of the

Table 1. Compact hybrid coupler comparative analysis.

Parameter	Simulation results (dB)	Measurement results (dB)
S_{11}	33.78	28.11 dB
S_{21}	$3.21\angle 87.35^\circ$	$3.83\angle -92.03^\circ$
S_{31}	$3.43\angle -2.84^\circ$	$3.30\angle 178^\circ$
S_{41}	34.7	19.20
Phase difference	-90.19°	-90.30°

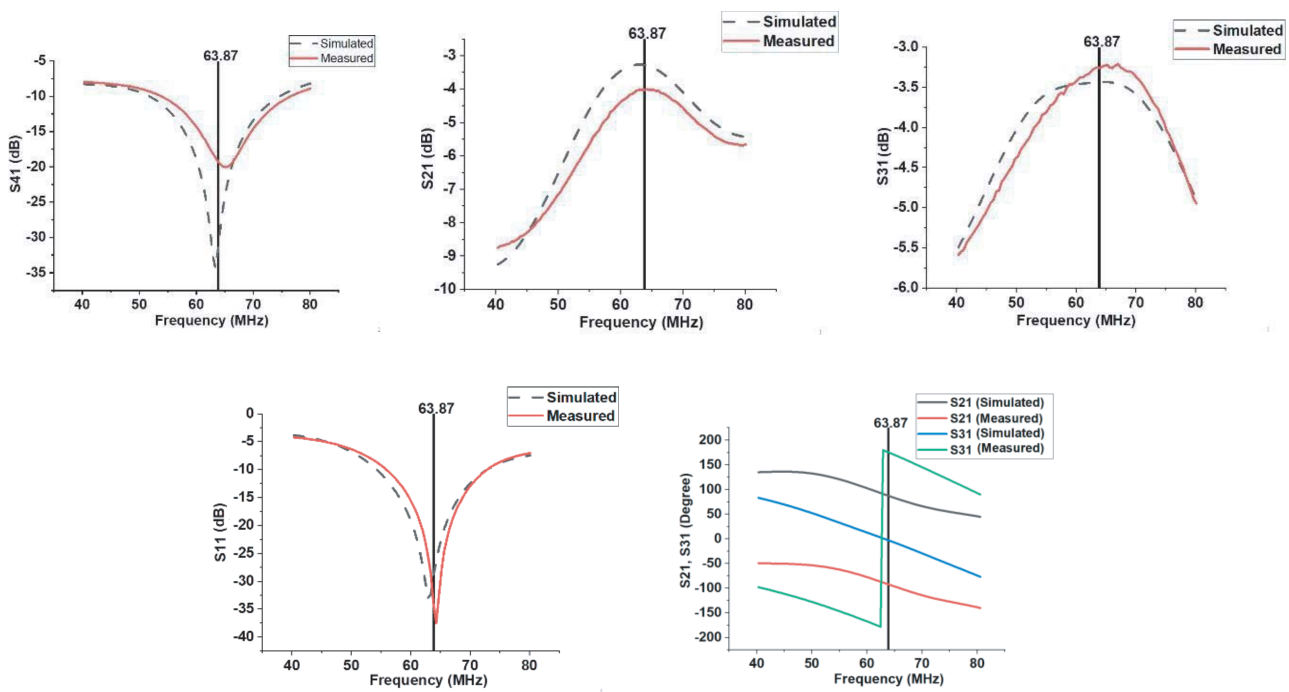


Figure 6. Simulated and measured of S and phase difference parameters of the flexible hybrid coupler.

cable and the capacitors were all kept the same. A photograph of the flexible hybrid coupler prototype is shown in Fig. 5(b).

The flexible hybrid coupler is then characterized using a Network Analyzer, and its results are compared with a rigid hybrid coupler using Origin software. It is observed that there is a minimal difference in parameters between rigid and flexible structures. S parameters and phase angle measurement of the flexible coupler are compared with the simulated one and are shown in Fig. 6.

Measured results of both compact and flexible hybrid couplers are summarized in Table 2. From the table, it is clear that the hybrid coupler can almost equally split power at its output port with a phase angle of 90° and that the two structures show close resemblance in the results. As a result, either of the two structures can be used as per convenience.

6.1. Deformation in Flexible Coupler

Deformation in coaxial cable can occur both mechanically or electrically. Crimp, kink, bending of cable beyond a certain limit causes mechanical deformation. If a very high-power signal passes through coaxial cable, then electrical deformation takes place. In both cases, dimensions of cable changes and hence its characteristic impedance alter from its original value which results in degradation of reflection coefficient and hence return loss hybrid coupler. At very high power, this degradation in reflection coefficient may

Table 2. Flexible hybrid coupler comparative analysis.

Parameter	Measurement results (dB) (compact coupler)	Measurement results (dB) (flexible coupler)
S_{11}	28.11	39.26
S_{21}	$3.83\angle-92.03°$	$3.89\angle-98.69°$
S_{31}	$3.30\angle 178°$	$3.18\angle 172.49°$
S_{41}	19.20	19.54
Phase difference	−90.30°	−91.18°

damage source due to reflected power from discontinuity. As per the study conducted by Karthik and Jayanthu [20] with coaxial cable RG-06 (Z_0 being 75 ohm), mechanical deformation of 0 to 4.4 mm takes place because of high pressure load from 0 to 1200 Kg. These results in a change of reflection coefficient from 0.135 to 0.91. Similar results showing direct proportionality between reflection coefficient and deformation are also reported by Dowding et al. [21]. An electrical kind of deformation is also reported in [22] which shows that radial deformation (expansion in diameter by 1.26 mm in the center conductor of coaxial cable) can take place when a pulsating current of amplitude 142 kA is sent through the cable. So, in a flexible hybrid coupler care requires to be taken to avoid any kind of deformation which will not degrade the performance of the coupler.

Presented work has also been compared with the work reported in literature for different designs of hybrid coupler, and it is presented in Table 3. In [18], reduction was reported around 80%, but there is a vast gap between measured and simulated results. It may be due to high frequency effect. Compared with past research work, the presented design shows close resemblance between simulated and measured results and good reduction of around 68% compared to conventional hybrid coupler.

Table 3. Comparative analysis of literature work with presented work.

Reference	Microwave Circuit	Operational frequency	Fabrication technique	% reduction in length w.r.t. conventional coupler
9	QHC*	175 MHz	Stripline	52.68%
10	QHC	175 MHz	Stripline	53.80%
11	3 dB RRHC**	260 MHz	Coaxial cable	96.6% but no reduction in physical length
15	3 dB HC***	3.5 GHz	microstrip line	62%
16	3 dB HC	3.5 GHz	Microstrip line	68.32%
18	3 dB HC and RRHC	25 GHz	Uniplanar MMIC	80% but vast gap between simulated and measured data
Presented work	3 dB HC	68.87 MHz	Coaxial cable	68%

*QHC — Quadrature Hybrid Coupler
**RRHC — Rat-Race Hybrid Coupler
***HC — Hybrid Coupler

7. POWER HANDLING CAPACITY OF THE HYBRID COUPLER

The proposed design uses a coaxial cable, which has high power handling capacity compared with microstrip line and lumped elements, which are often used to fabricate hybrid couplers at lower frequencies. Using coaxial cable RG187 and high-power handling capacitor, the proposed circuit can handle high power up to 2 kW. If we replace the coaxial cable with a suitable cable and the suitable substrate with a high power rated one, then it is expected that the above design can handle even higher power, which is required in MRI applications to excite the body birdcage coil.

8. CONCLUSION

Hybrid coupler or other microwave devices can be made compact at low frequency by using capacitive loading principle. The proposed design reduces the size of the hybrid coupler by 68% compared with conventional design, and it can handle high power as the coaxial cable is used. Measurement results show nearly 3 dB coupling and phase difference of 90° at its output port. This hybrid coupler can be made flexible by removing the extra part of the substrate, which creates a space that later can be used for adding another circuitry. The proposed design can be used in an MRI application for feeding power to body coil, volume coil, or Quadrature surface coil.

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