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Design and development of 2 kW, 3 dB hybrid coupler for the prototype Ion Cyclotron Resonance Frequency (ICRF) system

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Abstract

Design and development of 2 kW, 3 dB tandem hybrid coupler for the frequency range of 155–225 MHz has been presented in this paper. The developed 3 dB coupler is to be used in a prototype of Ion Cyclotron Resonance Frequency (ICRF) system of Tokamak, which has been developed to test the resilience of ICRF network during continuously variable RF load excursions. The 3 dB coupler divides the RF power between two antennae of the prototype and protects the RF source by coupling of reflected power to the isolated port. The developed coupler shows excellent coupling flatness of -3 ± 0.3 dB over 38% of fractional bandwidth and also provides voltage standing wave ratio (VSWR) <1.3, isolation better than 32 dB and return loss better than 25 dB in full band. The presented work establishes a technique which can be useful for the development of high-power hybrid coupler in the range of high frequency (HF), very high frequency (VHF) and ultra high frequency (UHF).

Introduction

The high-power hybrid coupler is an important component of RF system and networks used in communication, defense, aerospace, broadcast, etc. [1–3]. It has an important application in the field of fusion tokamak. Tokamak is a magnetic confinement device, which is used to control and confine the high-temperature plasma to have a controlled fusion reaction for future energy generation. Inside tokamak, plasma is heated up to several tens of million degrees centigrade to achieve required rate of the fusion reaction. The Ion Cyclotron Resonance Frequency (ICRF) heating is one of the promising heating methods used in tokamak. The ICRF frequency varies from 20 to 120 MHz, which depends on various parameters inside the tokamak. The ICRF system allows continuous injection of RF power for the heating of plasma inside tokamak using antennae. Plasma presents a continuously variable load impedance in front of RF antenna. These variations are very fast and can be in the order of few 100 µs. To deliver the optimum power to the plasma, load impedance essentially has to be matched with source impedance. Therefore, the ICRF system of the tokamak has been developed to provide matching of plasma with the RF source. Schematic representation of the typical ICRF system used in SST-1 is shown in Fig. 1. It comprises various components like RF generator, 3 dB coupler, stubs, line stretchers, antennae, variable load, dummy load, etc. [4–7]. These components are utilized to get the required matching of plasma to source impedance. Here, a 3 dB coupler is used to divide the RF power between two antennae of the prototype and also provide the essential protection to the RF generator by coupling the reflected power at matched terminated isolated port. The 3 dB coupler has been installed in various tokamaks such as SST-1 [5, 6], DIII-D, ASDEX, JET (Joint European torus), KSTAR and Tore Supra [7–13]. Installation of 3 dB hybrid turned to make the system more efficient, reliable, and robust in terms of operational reliability.

The development of an efficient ICRF system with a high speed matching capability is still a current research interest. The real ICRF systems of tokamaks are spatially distributed in a very long distance and unreliable to incorporate frequent changes due to its large configuration. Therefore, a prototype of ICRF system is being developed. The prototype designed is scaled at low-power and five times frequency of real ICRF system. It helps to reduce the system size so that it can be incorporated in a test bench. The prototype is to be utilized for testing the various concepts/techniques in reference to achieve fast matching speed in ICRF system of tokamak.

The 3 dB hybrid coupler is an important part of the prototype ICRF system [14, 15]. The design and development of the strip-line-based hybrid coupler is presented in this paper. The 3 dB hybrid couplers with single coupled section are used for low-power applications due to the narrow coupling gap. Therefore, two 8.34 dB TEM broadside coupled strip-line sections in tandem are chosen to achieve 3 dB coupling and sufficient coupling gap. Also, air dielectric is used to minimize the insertion and other losses. The developed hybrid coupler has 2 kW

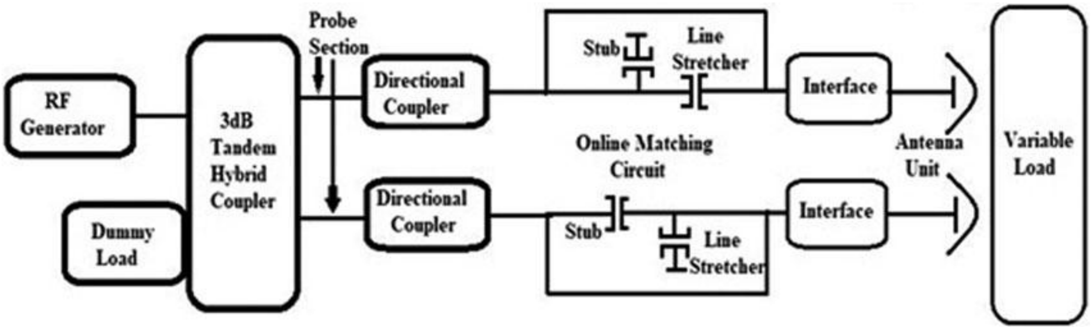

Fig. 1. Schematic representation of typical ICRF system.

power-handling capability and can be upgraded for higher as required in tokamak applications. It is performing excellently as power reflected (return loss S_{11}) from the input port is <0.3% (better than −25 dB) and isolation better than −32 dB for 155–225 MHz frequency band in test results. The work presents the design and developmental procedure of high-power hybrid coupler and strip-line components, which can be useful in various fields like tokamak, radar, satellite, etc. The paper is arranged as follow: section 'Analysis of coupled line section' describes the analysis of coupled line section, section 'Design of tandem hybrid coupler' explains the design of the tandem hybrid coupler, and section 'Fabrication and results' illustrates the fabrication process and results. Finally, a conclusion is drawn in section 'Conclusion'.

Analysis of coupled line section

The scattering matrix of the $\lambda/4$ length coupled line section is given as following:

$$S = \begin{bmatrix} 0 & -j\sqrt{1-c^2} & c & 0 \\ -j\sqrt{1-c^2} & 0 & 0 & c \\ c & 0 & 0 & -j\sqrt{1-c^2} \\ 0 & c & -j\sqrt{1-c^2} & 0 \end{bmatrix} \quad (1)$$

Where c represents coupling coefficient which depends on the even- and odd-mode impedanceZ_{0e} and Z_{0o} of coupled line section, respectively.

$$c = \frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}}. \quad (2)$$

For finite value of coupling coefficient c, $Z_{0e} \neq Z_{0o}$ are limited by the overall characteristic impedance Z_0, where

$$Z_0 = \sqrt{Z_{0e} \times Z_{0o}}. \quad (3)$$

The Z_{0e} and Z_{0o} mainly depend on the structural parameters of the coupled lines. For homogeneous coupled lines that are given by [16],

$$Z_{0e} = \frac{59.952\pi}{\sqrt{\varepsilon_r}} \frac{K(k')}{K(k)} \quad Z_{0o} = \frac{94.172\pi\, d/b}{\sqrt{\varepsilon_r}\tanh^{-1}(k)} \quad (4)$$

where $k' = \sqrt{1-k^2}$, $K(k')$ and $K(k)$ are the complete elliptic integrals of first kind. The value of $K(k^{'})/K(k)$ can be calculated by following [17]:

$$k = \left[1 - \left(\frac{0.5\exp^{\pi\frac{K(k)}{K(k')}} - 1}{0.5\exp^{\pi\frac{K(k)}{K(k')}} + 1}\right)^4\right]^{1/2} \text{ and}$$

$$\frac{w}{b} = \frac{2}{\pi}\left[\tanh^{-1}\sqrt{\frac{k - \frac{d}{b}}{1 - k\frac{d}{b}}} - \left(\frac{d}{b}\right)\tanh^{-1}\sqrt{\frac{k - \frac{d}{b}}{k\left(1 - k\frac{d}{b}\right)}}\right].$$

Here w, b, d, t, and ε_r repesent strip width, total hight of the conductor box, coupling gap, inner strip thinness, and relative permitivity of medium, respectively.

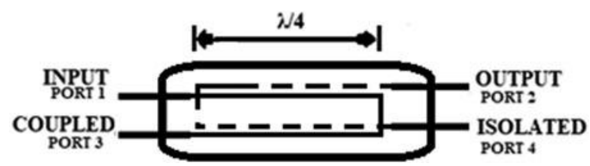

Fig. 2. Schematic representation of the 3 dB tandem hybrid coupler.

Design of tandem hybrid coupler

The schematic representation of the 3 dB tandem hybrid coupler is shown in Fig. 2. The RF power at input port-1 is equally divided between port-2 and port-3 with 90° out of phase, whereas port-4 is isolated. It is a symmetrical device and any one of the ports can be taken as an input port.

The tandem 3 dB hybrid coupler consists of two 8.34 dB coupled line sections connected in tandem for overall 3 dB coupling. The electrical length of the coupled line is taken as $\lambda/4$ at the center frequency, 182.5 MHz. The coupling coefficient c for 8.34 dB coupled lines corresponds to 0.3828 in linear scale. By substituting $c = 0.3828$ and $Z_0 = 50\ \Omega$ in equations (2) and (3), $Z_{0e} = 78.84\ \Omega$ and $Z_{0o} = 22.23\ \Omega$ have been calculated. The dimensions of the coupled lines section have been calculated using equation (4) for a given even- and odd-mode impedance. These are shown in Fig. 3(a) along with its perspective annotations. The 8.34 dB coupled lines sections are connected in tandem with non-coupled 50 Ω patch whose dimensions are calculated by using standard equations [16, 17]. The resulting dimensions of the patch are given in Fig. 3(b).

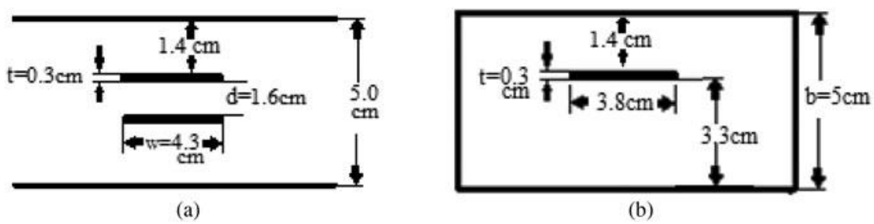

Fig. 3. Dimensions of coupled and patch section.

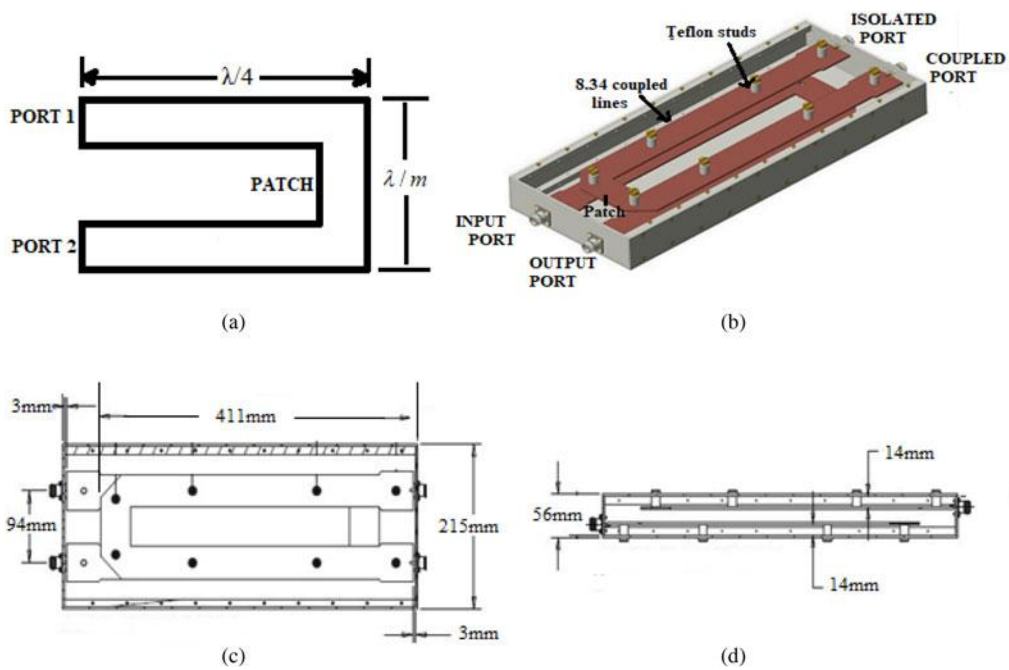

Fig. 4. Detailed assembly drawing of prototype tandem hybrid coupler. (a) *U*-shaped strip-line, (b) layout design, (c) top view, (d) side view of prototype coupler.

The detailed drawing of the designed hybrid coupler is shown in Fig. 4. The two identical *U*-shaped copper strip lines having opposite faces are hanged through outer ground metallic enclosure using Teflon studs. The resultant structure forms two 8.34 dB coupled line section by overlapping of strip line in each side. Both the 8.34 dB sections are connected in tandem with a small patch for overall 3 dB coupling. The degree of coupling is decided by the width of $\lambda/4$ section of coupled lines and the gap between the lines. Coupling gap of 8.34 dB coupled line section is selected in such a way that it can provide essential breakdown strength at 2 kW RF input. Air is used as a dielectric that provides space for heat dissipation and gives better average power handling in continuous wave application.

The designed model of hybrid coupler has been incorporated in CST microwave studio software. The simulation outcomes are shown in Fig. 5. The Figs 5(a)–5(d) present the coupling S_{31}, output S_{21}, return loss S_{11}, and isolation S_{41} parameters of the hybrid coupler, respectively. The coupling and output parameters are found as −3.001 and −3.031 dB at the center frequency, 182.5 MHz, and these are found under -3 ± 0.3 dB in an entire frequency band of 155–225 MHz. The return loss and isolation are found as −39 and −37 dB at the center frequency and are found better than −30 dB in an overall band.

The bandwidth of -3 ± 0.3 dB tandem coupler is approximately 38% at the center frequency of 182.5 MHz. Based on the simulation, we realized the bandwidth is greater than the single- and dual-section coaxial coupler as compared with the earlier study [11].

The electric field distribution inside the designed hybrid coupler is analyzed at 2 kW RF input using CST simulation. Simulation outcome is shown in Fig. 6. Here, the maximum electric field is found to be 6.6×10^4 V/m below the breakdown strength. The peak power-handling capability depends on various losses and the maximum value of an applied electric field. The maximum allowable electric field to prevent the break down is limited by 1.47×10^6 V/m. In simulation result, maximum electric field is found significantly less than the breakdown limit which verifies the maximum power rating of the coupler.

Fabrication and results

A photograph of the fabricated hybrid coupler is shown in Fig. 7. The fabricated hybrid coupler is having two *U*-shaped copper strip each of 3 mm thickness. The outer rectangular box with dimensions $51.7 \times 21.5 \times 5$ cm^{3}is designed with 3 mm-thick aluminum sheet where air is used as a dielectric. Teflon studs are used for the insulation of *U*-shaped copper strips and also to provide support for strip line in a metallic enclosure. Coaxial *N*-type connectors are applied for input–output terminals which can withstand high voltage.

The fabricated hybrid coupler is tested using a two-port Vector Network Analyzer (VNA). The prospective comparison of

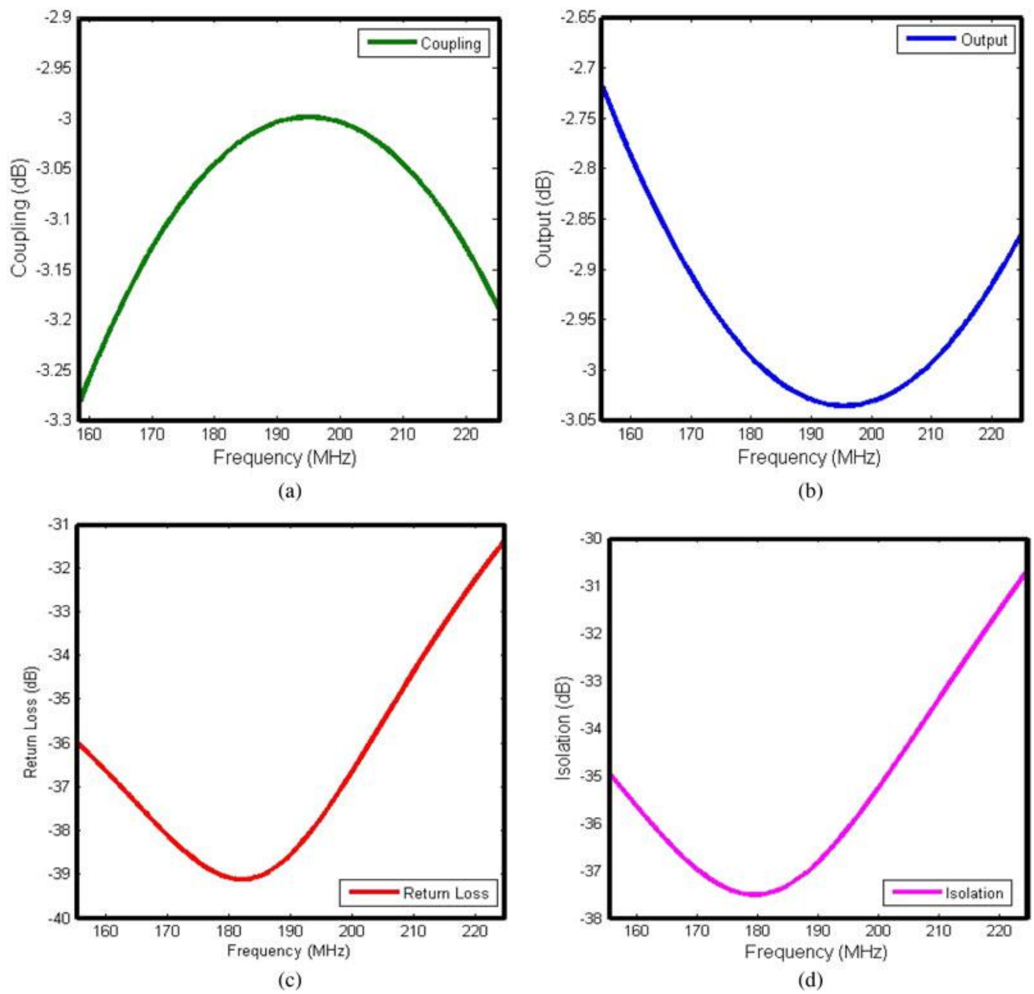

Fig. 5. Simulated *S*-parameters using CST software. (a) Coupling, (b) output, (c) return loss, and (d) isolation in dB.

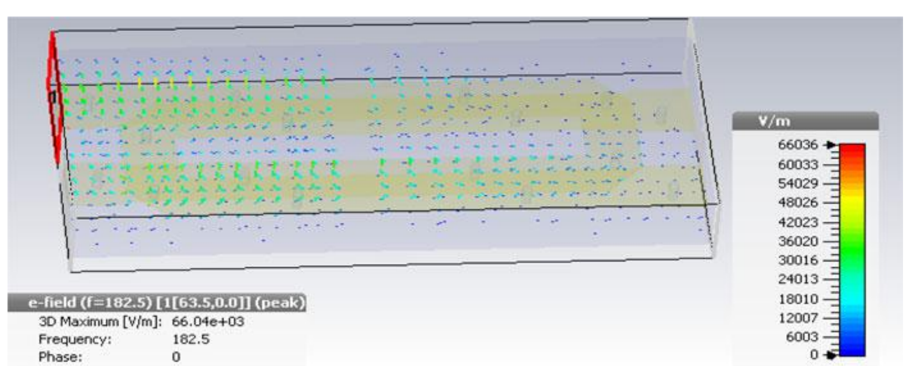

Fig. 6. Electric field plot of tandem hybrid coupler.

simulation and experimental results is shown in Fig. 8, where Fig. 8(a) shows coupling characteristic, Fig. 8(b) shows output, Fig. 8(c) shows return loss, and Fig. 8(d) shows isolation characteristics of the hybrid coupler. In simulation results, the coupling and output parameters are found as −3.001 and −3.031 dB, respectively, at the center frequency, 182.5 MHz, whereas the experimental results provide the coupling and output as −2.96 and −3.14 dB, respectively. The comparison shows that the test results are found in close agreement to the simulation results. In a given comparison, the coupling in test result is found slightly greater than simulation outcome. These differences are found as −3.001 and −2.96 dB in coupling, whereas −3.031 and −3.14 dB in output which can be due to the fabrication and material tolerances such as Teflon studs and heavy weight of copper strip line. The weight of copper strip lines also results in very small sagging when hanged over metallic enclosure using Teflon studs. The sagging introduces decrease in distance between the strip line. As the coupling coefficient is inversely proportional to the distance between the strip-line, these constraints have results with small differences between simulation and test results which

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Design and development of 3 dB patch compensated tandem hybrid coupler

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Design and development procedure of the strip line based 3 dB patch compensated tandem hybrid coupler at 91.2 ± 15 MHz and 2.5 kW is presented. The coupled strip-line structure is designed and electromagnetic analysis software is used for accurate modelling and optimization of parameters. Coupled strip lines are well known for poor impedance matching and poor isolation due to discontinuities, fabrication tolerance constraints, and theoretical approximations in design. These effects are realized and compensated or taken into consideration. The conventional methods of compensation like open stubs or lumped capacitors are useful in the low rf power applications only. In the present paper, patch compensation technique is explored, explained, applied, and incorporated in the development of a 3 dB tandem hybrid coupler. This newly explored patch compensation technique is found substantially effective in improving the overall performance in terms of return loss and isolation. A prototype tandem coupler rated for 2.5 kW at 91.2 ± 15 MHz, has been developed, fabricated, tested, and the effect of patch compensation technique is found to be quite effective. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4773538]

I. INTRODUCTION

In symmetrical 3 dB hybrid coupler input signal is equally divided to the output and coupled ports with a phase difference of 90°. This can be used as power combiner, power divider or to protect the rf source by coupling of reflected power to the isolated port. A hybrid coupler is an integral part of the rf systems like satellite communication, cellular, broadcast, defense, aerospace, etc. It has several useful applications in the rf and plasma related experiments also. The rf and plasma related small experiments are carried out at various frequencies from 10 to 100 MHz and up to 2.5 kW. The 3 dB hybrid coupler is required in some of the experiments to provide the rf power from one source to two electrodes in desired phase.

The ion cyclotron resonance heating (ICRH) system of tokamak uses continuous wave radio frequency (cwrf) of 100 kW onwards at ion cyclotron resonance frequency. Ion cyclotron resonance frequency varies from 10 to 100 MHz, which depends on geometry of the tokamak, desired plasma parameters, and toroidal magnetic field at the center of tokamak vessel. For example, in case of SST-1 tokamak 91.2 MHz frequency is required for ICRH during 2nd harmonics heating at 3 T tokamak operation.[1]

In a typical rf source, few mw of cwrf with desired modulation or pulsing is cascaded and after multistage amplification high power rf is obtained, which is introduced then into the tokamak with the help of two transmission lines. Output from the intermediate 2 kW rated pre-pre-driver stage of the cascaded multistage amplifier may be divided to drive two amplifier chains of high power output of 100 kW onwards each. These outputs can drive two antennae in the known phase or can be combined to drive one antenna whereas rf power output from one amplifier chain is not sufficient. Sometime, the rf power output of few MW is divided to drive two antennae that are arranged in a certain configuration. Thus, it has become imperative to understand, design, optimize, and indigenously develop the hybrid couplers for various plasma experiments in the frequency range of 10–100 MHz.

Therefore, in the first step, the development of 2.5 kW 3 dB hybrid coupler at 91.2 ± 15 MHz is selected. This prototype is aimed mainly to create a process of indigenous fabrication of 2.5 kW, 3 dB hybrid coupler at any required frequency from 10 to 100 MHz for plasma experiments, etc. The concept, design, and development procedure should also be applicable while making hybrid coupler of more than 100 kW power rating at the various frequencies within the range of 10–100 MHz.

Broadside TEM coupled strip-line structures are widely used as 3 dB couplers due to simple design, cost effectiveness, and ease of fabrication. The 3 dB Hybrid couplers with single coupled section are used for low power applications due to the narrow coupling gap.[2] Therefore, two 8.34 dB TEM broadside coupled strip-line sections in tandem are selected. Air dielectric is used to minimize the insertion and other losses. It renders the upgradation from prototype to high power application easier. TEM coupled strip lines are well known for poor impedance matching and poor isolation due to discontinuities, fabrication tolerance constraints, and theoretical approximations in strip lines. Isolation of strip-line couplers can be improved by introducing lumped or distributed capacitors at the edges or in the center of the coupled region.[3,4] In the broadside coupled strip-line couplers, capacitors are connected to the ground in shunt capacitive compensation technique.[5] Recently, Slawomir *et al.*[6] have presented the technique to compensate parasitic reactance of the coupled lines by connecting the shunt capacitances to both coupled and signal lines.

The conventional methods for the compensation use lumped capacitors or shunt open stubs that have limitations with high power application. Commercially available lumped

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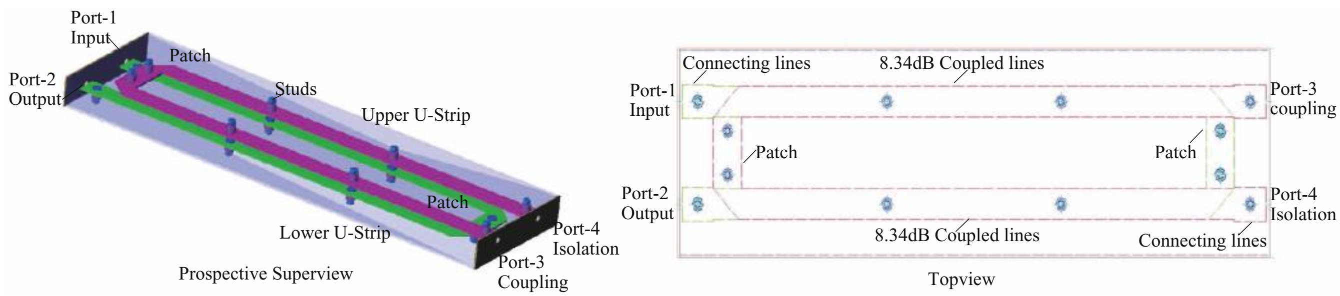

FIG. 1. Proposed tandem 3 dB hybrid coupler.

high power rf capacitors are large in size and lossy above 10 MHz frequency. Connecting shunt capacitor in coupled line affects the coupling and therefore compensation will be needed in the coupling gap also. If open stubs are used, high electric field exists on edges that may result in arcing.

In the present work, a novel patch compensation technique is explored for the 3 dB tandem hybrid coupler. It is observed that this technique enhances the performance of the coupled line circuit without using lumped capacitors and open stubs. This paper is arranged as follows.

Section II describes the concept, design, and optimization of the hybrid coupler, Sec. III explains the theory of patch compensation, and Sec. IV illustrates the power handling capability of the hybrid coupler. The fabrication process is described in Sec. V while test results are presented and discussed in Sec. VI. Finally, conclusion on the hybrid coupler with novel patch compensation technique are drawn in Sec. VII.

II. CONCEPT, DESIGN, AND OPTIMIZATION

The tandem 3 dB hybrid coupler is designed by connecting two 8.34 dB coupled lines in tandem. It consists of two rectangular strip-line central conductors that are arranged one above the other and placed in the grounded metallic enclosure as shown in Fig. 1. The design is divided into the coupled and non-coupled sections. The electrical length of the coupled line is taken as quarter wavelength at desired frequency with Z_{ce} and Z_{co} as the characteristic impedances for even and odd modes, respectively. Thus, 3 dB hybrid coupler design and fabrication procedure may be generalized to work for others frequencies also. The width of coupled lines and the gap between them decides the degree of coupling. The non-coupled sections are constituted with connecting signal lines and the patch of Z_0 characteristic impedance. The patch is a small segment ($\leq \lambda/15$) of strip line that is used to connect two 8.34 dB coupled strip lines in tandem. Air within the grounded metallic enclosure is used as dielectric and the strip line conductors are supported by teflon studs.

A. Coupled strip-line design

The 8.34 dB broad sided coupled strip lines of the tandem hybrid coupler are illustrated in Fig. 2. Here, t, w, d, and b represent the thickness, width, spacing between coupled lines, and the height of grounded box, respectively. An arbitrary excitation of coupled lines characteristic impedance Z_0 is treated as superposition of amplitudes of even and odd modes given by

$$Z_{ce} = Z_0\sqrt{\frac{1+C_v}{1-C_v}},\; Z_{co} = Z_0\sqrt{\frac{1-C_v}{1+C_v}},$$

which gives

$$Z_0 = \sqrt{Z_{ce}Z_{co}}. \tag{1}$$

Here, Z_{ce} and Z_{co} are the coupled lines characteristic impedances of coupled lines for even and odd modes, respectively. For 8.34 dB coupled lines, the value of coupling coefficient C_v corresponds to 0.3828. For $Z_0 = 50\,\Omega$ impedance Z_{0e} is 78.84 Ω and Z_{0o} is 22.23 Ω. In order to calculate Z_{0e} and Z_{0o} we have used following equations which are given by Cohn:[7]

$$Z_{ce} = \frac{59.952\pi}{\sqrt{\epsilon_r}}\frac{K(k')}{K(k)}, \tag{2}$$

$$Z_{co} = \frac{94.172\pi(d/b)}{\sqrt{\epsilon_r}\tanh^{-1}(k)}, \tag{3}$$

$$\text{where } k = \left[1-\left(\frac{0.5\exp^{\pi\frac{K(k)}{K(k')}}-1}{0.5\exp^{\pi\frac{K(k)}{K(k')}}+1}\right)^4\right]^{1/2}, \tag{4}$$

$$\frac{w}{b} = \frac{2}{\pi}\left[\tanh^{-1}\sqrt{\frac{\left(k-\frac{d}{b}\right)}{\left(1-k\frac{d}{b}\right)}} - (d/b)\tanh^{-1}\sqrt{\frac{\left(k-\frac{d}{b}\right)}{k\left(1-k\frac{d}{b}\right)}}\right], \tag{5}$$

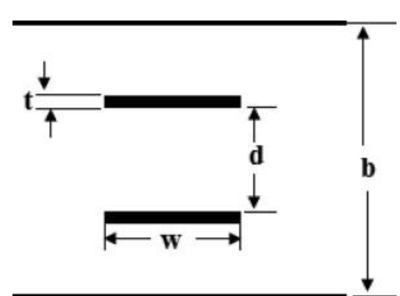

FIG. 2. Schematic diagram single 8.34 dB coupled strip line.

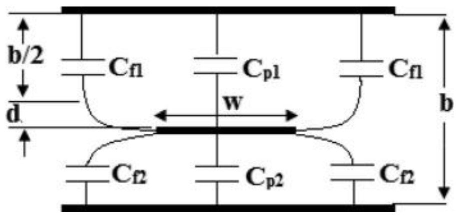

FIG. 3. Strip line with off-set rectangular strip.

where $k' = \sqrt{1-k^2}$ and $K(k')$, $K(k)$ are the complete elliptic integrals of first kind. The value of $K(k')/K(k)$ can be found in Ref. 8 and references therein that gives Z_{oe} and Z_{0o} for the specified value of d/b and w/b. Using $b = 5$ cm in above equations, we get strip-width $w = 4.125$ cm and $d = 2.475$ cm. From the above Eqs. (3) and (5), it can be seen that all design parameters are calculated in terms of ratio d/b and w/b. That means, w and d are dependent upon b that is calculated for the required power rating. The value of b as explained in Sec. IV is 5.0 cm for the 2.5 kW rated prototype. Therefore, the device can be upgraded in terms of power by increasing b, w, and d as shown by the Eqs. (2) and (5).

B. Non-coupled strip-line design

With certain approximations, one can provide (see Ref. 8 and references therein) the relationship of characteristic impedance with the shunt capacitances of homogeneous strip line placed at arbitrary distance from the ground plane as shown in Fig. 3. The characteristic impedance Z_0 is given as

$$Z_0 = \frac{376.7\sqrt{\epsilon_r}}{C_t}, \tag{6}$$

where ϵ_r is dielectric constant of the substrate and C_t is total capacitance, given by

$$C_t = C_{p1} + C_{p2} + 2C_{f1} + 2C_{f2}.$$

Note that C_{p1} is face capacitance on upper side, C_{p2} is face capacitance on lower side, C_{f1} is fringing capacitance on upper side, and C_{f2} is fringing capacitance on lower side. These are expressed as

$$C_{p1} = \epsilon_r \left(\frac{2\frac{w}{b-2d}}{1 - \frac{t}{b-2d}} \right), \tag{7}$$

$$C_{p2} = \epsilon_r \left(\frac{2\frac{w}{b+2d}}{1 - \frac{t}{b+2d}} \right), \tag{8}$$

$$C_{f1} = \frac{\epsilon_r}{\pi} \left[\frac{1}{1-\frac{t}{b-2d}} \ln\left(\frac{1}{1-\frac{t}{b-2d}} + 1 \right) - \left(\frac{1}{1-\frac{t}{b-2d}} - 1 \right) \ln\left(\frac{1}{\left(1-\frac{t}{b-2d}\right)^2} - 1 \right) \right], \tag{9}$$

$$C_{f2} = \frac{\epsilon_r}{\pi} \left[\frac{2}{1-\frac{t}{b+2d}} \ln\left(\frac{1}{1-\frac{t}{b+2d}} + 1 \right) - \left(\frac{1}{1-\frac{t}{b+2d}} - 1 \right) \ln\left(\frac{1}{\left(1-\frac{t}{b+2d}\right)^2} - 1 \right) \right]. \tag{10}$$

In our case, for the design of 3 dB tandem, connecting lines are 0.8 cm away from the center, therefore, $2d = 1.6$ cm, $b = 50$ cm, $Z_0 = 50\,\Omega$, $t = 0.3$ cm, and $\epsilon_r = 1$ give $w = 5.75$ cm. These dimensions and the effect due to teflon studs are optimized by using HFSS software and performance has been calculated in term of S-parameters. The optimized design dimensions are shown in Fig. 4. For these optimized dimensions, a tandem 3 dB hybrid coupler has been fabricated and tested with VNA. HFSS optimized design results and the measured S-parameters without compensation are shown in Fig. 5. It can be seen that the measured values of return loss and isolation are inferior due to the fabrication tolerance constraints and theoretical approximations in design. Therefore, compensation is required for overall better performance. A novel idea of patch compensation technique has been explored as illustrated in Sec. III.

III. PATCH COMPENSATION THEORY

The terminology used with a U-shaped coupled strip line and its equivalent circuit is shown in Fig. 6. where Z_c and Y_c are coupled lines impedance and admittance, Z_m and Y_m are patch impedance and admittance, Z_0 and Y_0 are the characteristic impedance and admittance of the system, Z_{in} and Y_{in} are transform impedance and admittance at point A, β is propagation constant, and $l = \lambda/m$ is patch length. Admittance transformation equation is given as

$$Y_{in} = Y_m \frac{Y_c + jY_m\beta l}{Y_m + jY_c\beta l}. \tag{11}$$

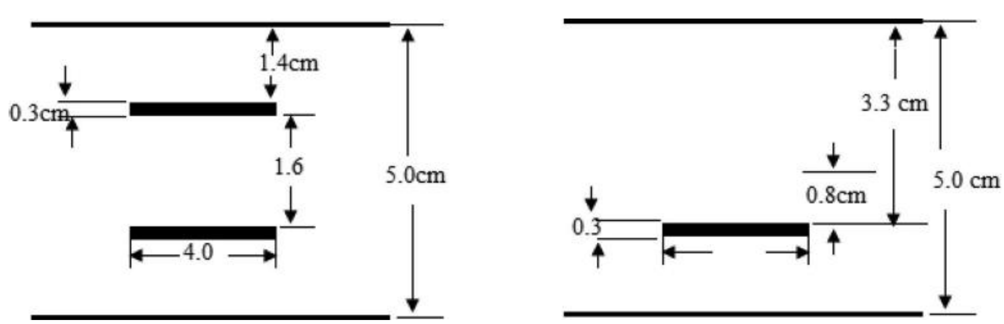

FIG. 4. Final dimension of the coupled and non-coupled line sections.

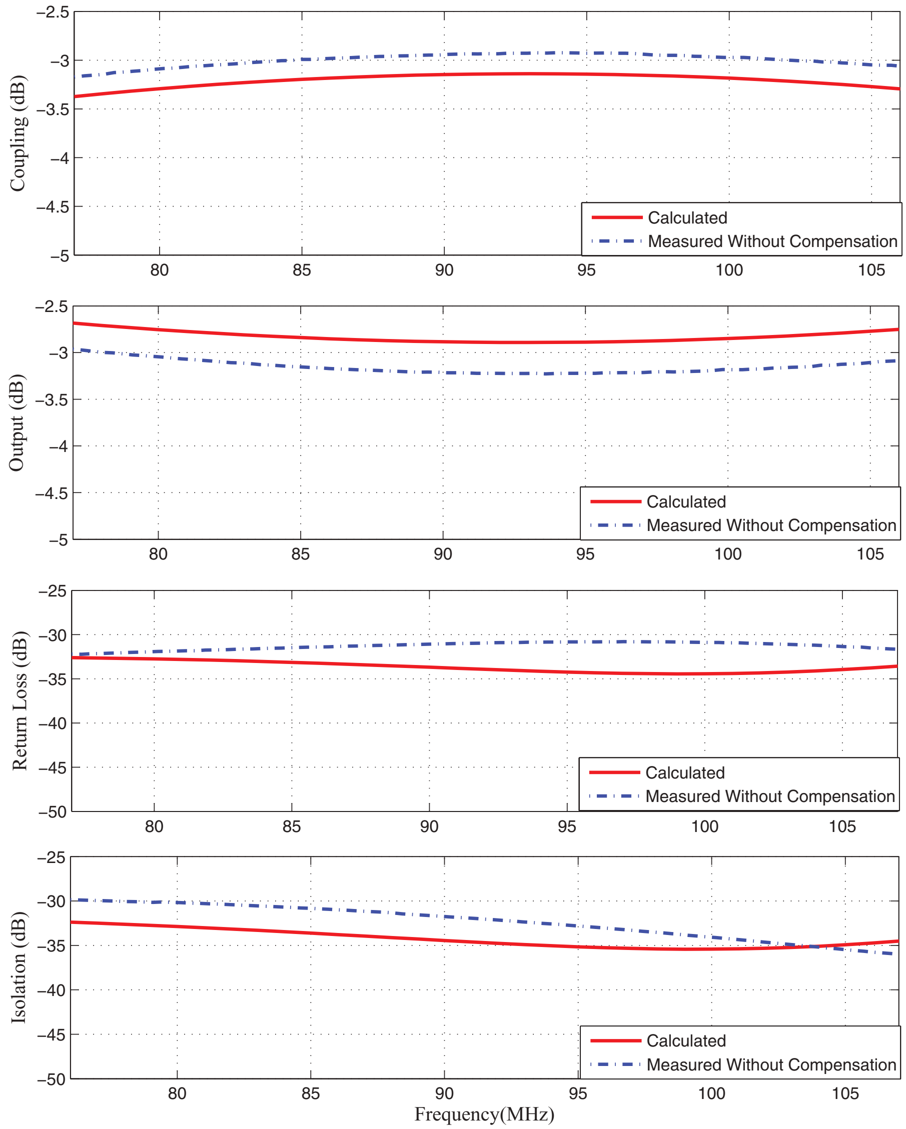

FIG. 5. HFSS optimized design results and the measured S-parameters without compensation.

For the small section of high impedance, i.e., $Y_c \leq 1$ and $\beta l \ll 1$, it implies $Y_c \beta l \lll 1$. This gives

$$Y_{in} = Y_c + jY_m \beta l. \tag{12}$$

Thus, a small line section behaves like shunt capacitance of $Y_m \beta l/\omega$ F. Therefore, the resulting equivalent circuit of the single strip line of the tandem coupler is as shown in Fig. 7.

The corresponding transmission matrix is

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_c \\ \frac{j}{Z_c} & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y'_m & 1 \end{bmatrix} \begin{bmatrix} 0 & jZ_c \\ \frac{j}{Z_c} & 0 \end{bmatrix}$$
$$= \begin{bmatrix} -1 & -Z_c{}^2 Y'_m \\ 0 & -1 \end{bmatrix}, \tag{13}$$

where patch is replaced with lumped admittance of $Y'_m = Y_m \beta l = Y_m \beta \lambda/m$.

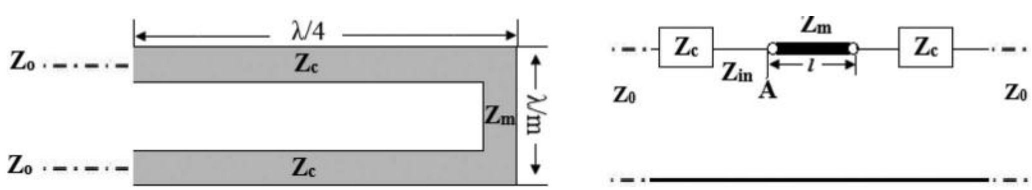

FIG. 6. U-shaped coupled strip line and equivalent circuit diagram.

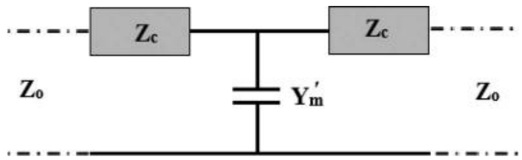

FIG. 7. Equivalent circuit diagram of strip line of tandem coupler.

The transmission matrix for matched U-shaped strip line of length ($\lambda/2 + \lambda/m$) can be written as

$$\begin{bmatrix} \cos(\pi+\beta\lambda/m) & jZ_0\sin(\pi+\beta\lambda/m) \\ j\sin(\pi+\beta\lambda/m)/Z_0 & \cos(\pi+\beta\lambda/m) \end{bmatrix} = \begin{bmatrix} -1 & jZ_0\beta\lambda/m \\ j\beta\lambda/mZ_0 & -1 \end{bmatrix}. \tag{14}$$

Comparing Eqs. (13) and (14) for $m \geq 15$ and by considering, $j\beta\lambda/mZ_0 \ll 1 \cong 0$, we get

$$Y_m = \frac{-JZ_0}{{Z_c}^2}. \tag{15}$$

This shows that Y_m is capacitive for $m > 15$. HFSS software is used to optimize hybrid coupler dimension for port impedance of $Z_0 = 50\,\Omega$. On this basis, it is fabricated, tested with VNA and found that the port impedance $Z_c = 56\,\Omega$. This deviation is due to the discontinuities, fabrication tolerance constraints, theoretical approximations in strip lines, etc. From Eq. (15), we get

$$|Y_m| = \frac{Z_0}{{Z_C}^2} = \frac{50}{56^2} = 0.0159, \quad \text{i.e.,} \quad Z_m = 62.72\,\Omega. \tag{16}$$

Therefore, the patch impedance should be 62.72 Ω for matching the coupled strip lines to the port impedance. The proposed compensation technique should improve the performance without affecting the coupling characteristic. The width of patches is calculated to be altered from 4.4 cm to 3.6 cm, i.e., 50 Ω to 62.72 Ω impedance. As all ports are quarter wavelength away from patches, therefore, $Z_m = 62.72\,\Omega$ of the patch is expected to match the coupled strip line $Z_c = 56\,\Omega$ to the port impedance $Z_0 = 50\,\Omega$ by quarter wavelength transformer action.

Patch compensation also improves the isolation characteristic as presented here analytically. Using Eq. (13), we get

$$\begin{bmatrix} \bar{A} & \bar{B} \\ \bar{C} & \bar{D} \end{bmatrix} = \begin{bmatrix} -1 & -{\bar{Z}_c}^2\bar{Y}'_m \\ 0 & -1 \end{bmatrix}, \tag{17}$$

where $\bar{A}$, $\bar{B}$, $\bar{C}$, and $\bar{D}$ represent the normalized transmission matrices parameters.

For the coupled lines impedance Eq. (1) gives $\bar{Z}_c = \sqrt{\bar{Z}_{ce}\bar{Z}_{co}}$, where $\bar{Z}_{ce}$ and $\bar{Z}_{co}$ are the normalized even and odd mode impedances of the coupled section. In order to calculate transmission matrix parameters of the coupled lines for the even and odd mode are given as

$$\bar{Z}_{ce} = q\bar{Z}_c \text{ and } \bar{Z}_{co} = \frac{\bar{Z}_c}{q}, \text{ where } q = \sqrt{\frac{\bar{Z}_{ce}}{\bar{Z}_{co}}}. \tag{18}$$

By the application of Eqs. (17) and (18) even and odd mode transmission matrices for U shaped patched compensated strip line are given as

$$\begin{bmatrix} \bar{A}_e & \bar{B}_e \\ \bar{C}_e & \bar{D}_e \end{bmatrix} = \begin{bmatrix} -1 & -q^2{\bar{Z}_c}^2\bar{Y}'_m \\ 0 & -1 \end{bmatrix} \text{ and } \begin{bmatrix} \bar{A}_o & \bar{B}_o \\ \bar{C}_o & \bar{D}_o \end{bmatrix} = \begin{bmatrix} -1 & -\frac{{\bar{Z}_c}^2}{q^2}\bar{Y}'_m \\ 0 & -1 \end{bmatrix}. \tag{19}$$

The amplitude of the emerging power A_4 from the isolated port-4, is given as

$$A_4 = \frac{1}{2}\left[T_{0e} - T_{0o}\right], \tag{20}$$

where T_{0e} and T_{0o} are the amplitudes of transmitted waves, for the even and odd modes for two-port networks, respectively. These are given as

$$T_{0e} = \frac{2}{\bar{A}_e + \bar{B}_e + \bar{C}_e + \bar{D}_e} \text{ and } T_{0o} = \frac{2}{\bar{A}_0 + \bar{B}_0 + \bar{C}_0 + \bar{D}_0}. \tag{21}$$

By using Eqs. (19)–(21) power coming at isolated port-4 of 3 dB patch compensated tandem coupler is obtained as

$$A_{4c} = \frac{x(q^4-1)}{(2q^2+x)(q^2+2x)} \text{ where } x = \bar{Z}_c^2\bar{Y}_m\beta l, \tag{22}$$

where A_{4c} is the amplitude of power that appears at isolated port-4. For the small patches $0 \leq \bar{Z}_c^2\bar{Y}_m\beta l \leq 1$, this means $0 \leq x \leq 1$, for all $\bar{Z}_c$ and $\bar{Y}_m$.

Before patch compensation, impedance of patches is taken as characteristic impedance ($\bar{Z}_0 = 1$). For the analysis of power emerging at isolated port-4 of uncompensated tandem coupler transmission matrix for the U-shaped strip line can be written as

$$\begin{bmatrix} \bar{A} & \bar{B} \\ \bar{C} & \bar{D} \end{bmatrix} = \begin{bmatrix} 0 & j\bar{Z}_c \\ j/\bar{Z}_c & 0 \end{bmatrix}\begin{bmatrix} \cos\beta l & j\sin\beta l \\ j/\sin\beta l & \cos\beta l \end{bmatrix}\begin{bmatrix} 0 & j\bar{Z}_c \\ j/\bar{Z}_c & 0 \end{bmatrix} = \begin{bmatrix} 0 & -j{Z_c}^2\sin\beta l \\ -j/({Z_c}^2\sin\beta l) & 0 \end{bmatrix}. \tag{23}$$

For short length patches $\beta l \ll 1$ and therefore $\sin\beta l = \beta l$. By using Eqs. (20), (21), and (23) power emerging at port-4 of uncompensated coupler is derived as

$$A_{4wc} = \frac{r^2(q^8-1)}{(q^4+r^2)(1+q^4r^2)} \text{ where } r = {\bar{Z}_c}^2\beta l. \tag{24}$$

Here, A_{4wc} is amplitude of power that appears at isolated port-4 of uncompensated coupler. For the small patches $0 \leq {\bar{Z}_c}^2\beta l \leq 1$, that means $0 \leq A \leq 1$, for all $\bar{Z}_c$.

From Eq. (18), for 8.34 dB coupled lines of the tandem coupler, q = 1.51. Using Eqs. (22) and (24) A_{4wc} and A_{4c} are plotted for $0 \leq A \leq 1$ and $0 \leq x \leq 1$ in Fig. 8. From Fig. 8, it is found that A_{4c} is less than A_{4wc} for the interval. It means that the isolation characteristic should also be effectively improved after compensation.

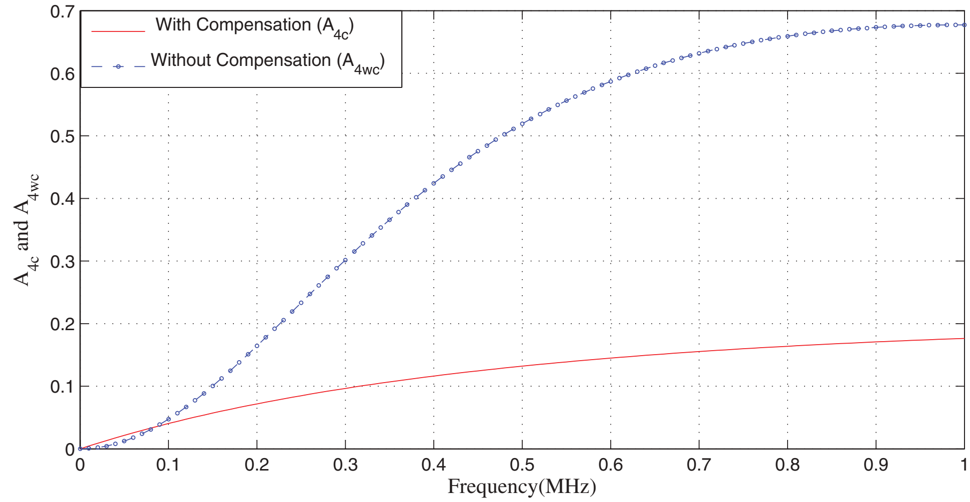

FIG. 8. Analytic comparison of isolation of compensated and uncompensated hybrid coupler.

It is well known that optimization of the lumped or distributed capacitors at the edges or in the center of the coupled region of the strip-line couplers improves the isolation characteristic. Patches behave as lumped capacitors and they are directly connected to the coupled lines of the tandem coupler. Therefore, isolation performance of the hybrid coupler is improved.

IV. ESTIMATION OF POWER HANDLING CAPABILITY

Power handling capability P_o of the designed 3 dB hybrid coupler is limited by various losses and the peak voltage at strip conductor. Hybrid coupler uses air as dielectric with breakdown voltage rating of 3×10^4 V_{dc}/cm or $1.47 \times 10^4 V_{rf(peak)}$/cm.[9] In the presence of standing waves, this becomes $(1.47/2) \times 10^4 V_{rf(peak)}$/cm, i.e., equivalence ratio of 4.1 with respect to dc breakdown voltage. In this design, the hybrid coupler strip conductor clearance is 1.4 cm from the ground. Therefore,

$$P_o = \frac{{V_{peak}}^2}{2Z_0} = 1.0588 \times 10^6 \mathrm{W}.$$

The teflon studs that hold strip conductor are tested for surface peak breakdown strength of 2 kV_{dc} which is equivalent to 0.49 $kV_{rf(peak)}$. This limits the hybrid coupler to the rating of 2.5 kW because

$$P_o = \frac{\left(4.9 \times 10^3\right)^2}{2 \times 50} = 2.5 \times 10^3 \text{ W}.$$

Average power handling capability (P_{av}) of the strip line, i.e., optimization of the dielectric loss and ohmic losses with the dissipation capability can be written as

$$P_{av} = \frac{60\pi g \left(T_{max} - T_s\right)}{\Delta T \left(\alpha_{ic} - \alpha_{id}\right) Z_0 \sqrt{\epsilon_r}},$$

where T_s (strip-line temperature) = ambient 35 °C, T_{max} (maximum allowable operating temperature) = 45 °C, g (thermal conductivity for air) = 0.0278 $w/m\,k$, $\epsilon_r = 1$,

$$\alpha_{ic} \text{ (conductor loss coefficient)} = \frac{2.7 \times 10^{-3} R_s \epsilon_r Z_0}{30\pi\,(b-t)} \times \left[1 + \frac{2w}{b-t} + \frac{(b+t)\,Z\sqrt{\epsilon_r}}{\pi\,(b-t)} \ln\left(\frac{2b-t}{t}\right)\right].$$

For R_s (skin resistance) = 2.4925×10^3 Ω/m, w (strip width) = 0.044 m, b (ground conductor box height) = 0.05 m, and t (strip thickness) = 0.003 m, we get,

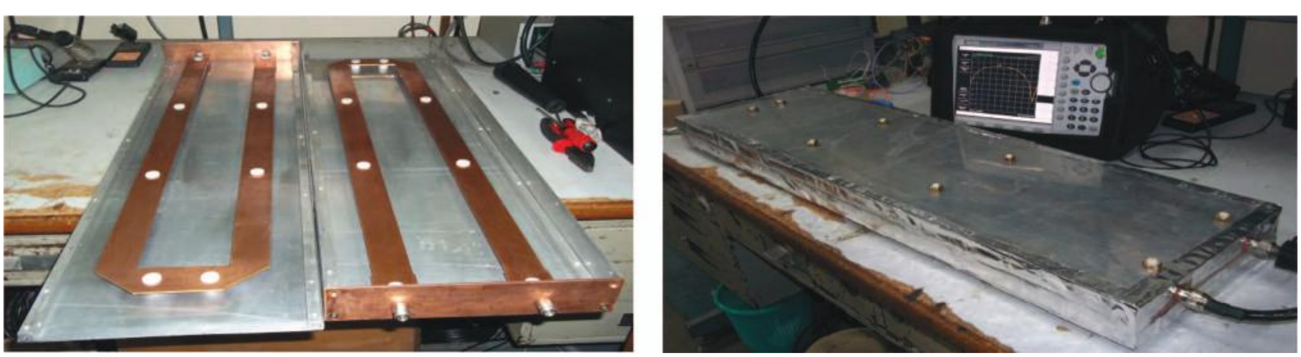

FIG. 9. Photograph of the fabricated hybrid coupler.

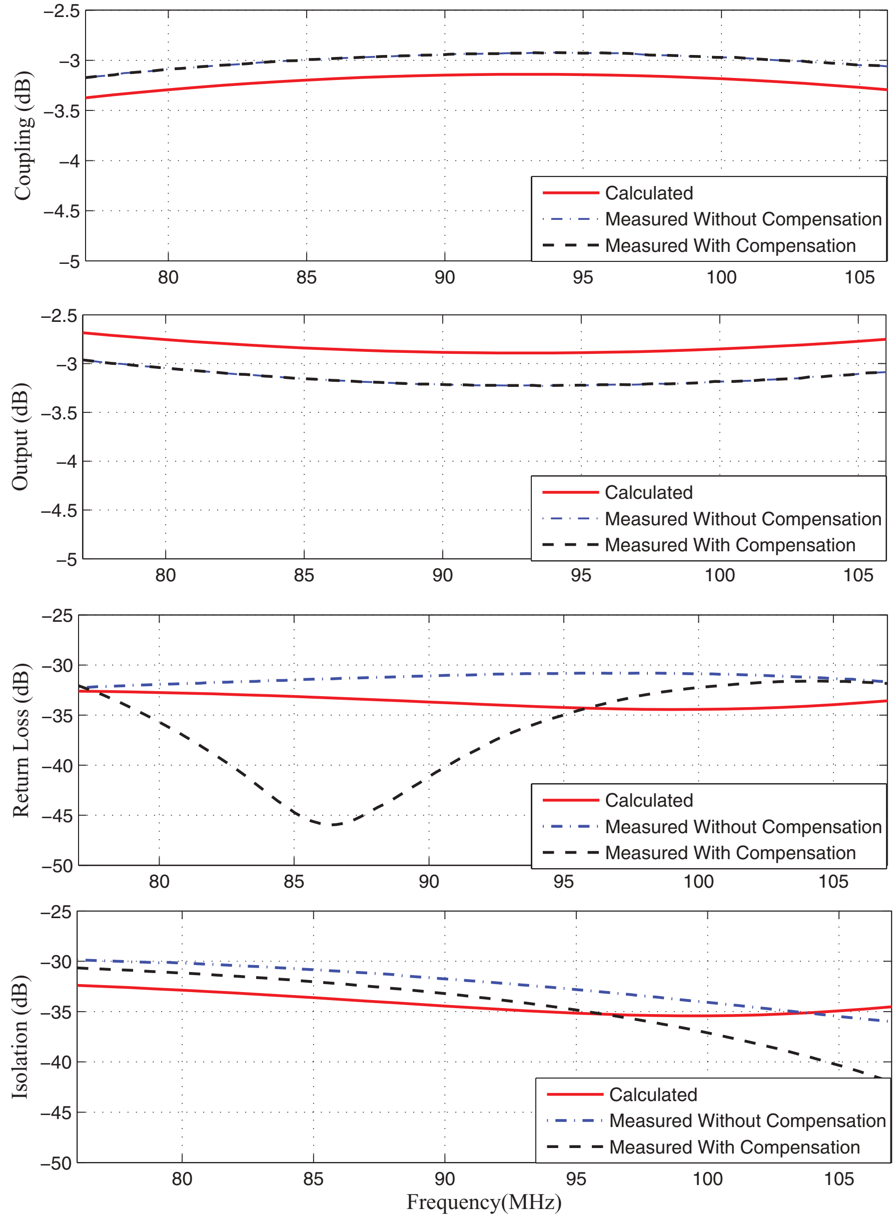

FIG. 10. Comparison of HFSS optimized design results, the measured S-parameters without compensation and with compensation.

$\Delta T = 2.988 \times 10^{-3}$ °C/w, $\alpha_{ic} = 3.13 \times 10^{-4}$ Np/m, and therefore, $P_{av} = 3.3$ kW.

The design of fabricated hybrid coupler was aimed at 2.5 kW rating and the teflon studs comply with the same. Power handling capability of fabricated hybrid coupler may be extended up to 3.3 kW by replacing studs of same rating.

V. FABRICATION PROCESS

Designed hybrid coupler is fabricated with two U-shaped 3 mm thick copper strip-line conductors that are overlapping in opposite directions. The strip-widths of the coupled and non-coupled sections are 4.0 cm and 4.4 cm, respectively. Outer conductor rectangular box of dimensions 99.2 × 26.4 × 5.0 cm^3 is fabricated with the aluminum sheet of thickness 0.3 cm. A photograph of the fabricated hybrid coupler assembly is shown in Fig. 9. Patch compensation is applied after testing the hybrid coupler with VNA.

VI. RESULTS AND DISCUSSION

In the present work, a hybrid coupler is designed and optimized with HFSS for coupling of −3 ± 0.2 dB, output of −3 ± 0.2 dB, return loss of less than −32 dB, and isolation of better than −32 dB in the frequency range of 91.2 ± 15 MHz. The same is also optimized for return loss of −34 dB and isolation of −34 dB at the center frequency 91.2 MHz. Hybrid coupler is tested with VNA and found providing coupling of −3 ± 0.2 dB, output of −3 ± 0.2 dB, return loss of less than −30.5 dB and isolation of better than −30 dB in the given frequency range. The same is found providing the return loss of −31 dB and isolation of −32 dB at the center frequency 91.2 MHz. Comparison of measured values with

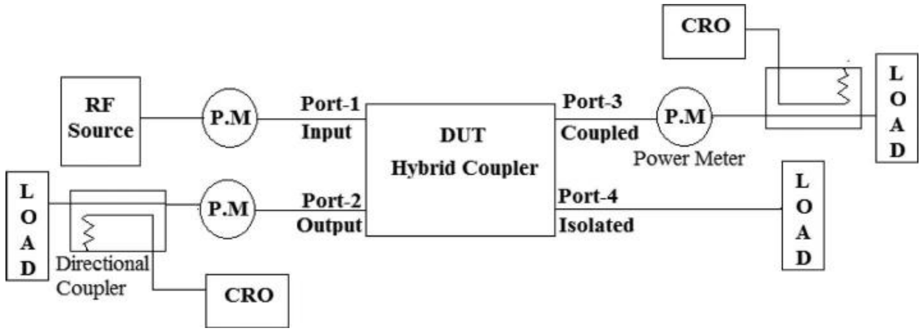

FIG. 11. Schematic diagram of high power test setup.

the calculated parameters is shown in Fig. 5. This implies that improvement is needed.

The proposed compensation technique is implemented in the designed and fabricated hybrid coupler. The modified, i.e., patch compensated hybrid coupler is tested and found providing coupling of -3 ± 0.2 dB, output of -3 ± 0.2 dB, return loss of less than -32 dB, and isolation of better than -31 dB in the given frequency range. The same is found providing the return loss of -40 dB and isolation of -33 dB at the center frequency 91.2 MHz. Thus, the performance is observed greatly improved after compensation as shown in Fig. 10.

In case of return loss, great improvement is observed at the center frequency as this compensation technique is frequency sensitive and uses the concept of quarter wavelength transformer matching, whereas the isolation is improved uniformly within the given frequency range due to lumped capacitive behavior of the patches. The resulting coupling, output, return loss, and isolation in the given frequency range imply 2.120 W of heat dissipated for input power of 2.5 kW, i.e., $0.067\,^{\circ}\mathrm{C/min}$ increase of the strip-line temperature at $35\,^{\circ}$C ambience. Estimated thermal equilibrium is found established at about $38\,^{\circ}$C.

The cwrf high power test is conducted with the available 1 kW rated source for 8 h without interruption. Schematic diagram of cwrf high power test setup and the resulting waveforms at the coupled and output port are shown in Figs. 11 and 12, respectively. Power meters connected with ports 1, 2, and 3 give the actual power measurement. Directional coupler and the oscilloscope are connected to obtain sample of forward going power at the coupled and output ports. The performance confirms to VNA testing.

Voltage withstanding level at each of the ports and between the coupled lines is found 2 kV dc as measured with a breakdown tester. This confirms the operational capability at 2.5 kW of the patch compensated 3 dB hybrid coupler.

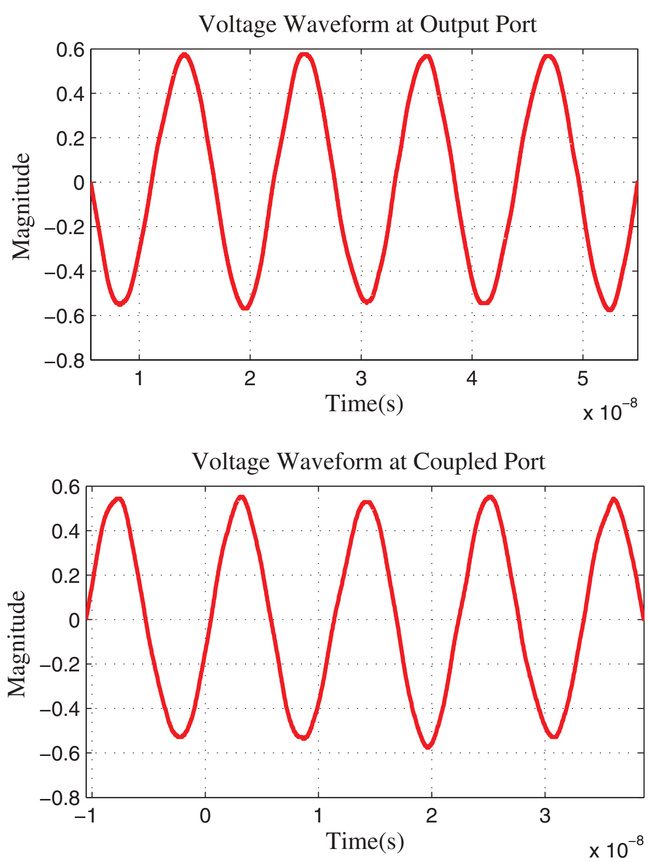

FIG. 12. Measured voltage waveforms at coupled and output port at 1.0 kW input.

VII. CONCLUSION

In the following, we discuss the main conclusions of the present work.

- A novel patch compensation technique is developed to enhance the performance of tandem hybrid coupler without using lumped capacitors and open stubs. A procedure has been established for the calculation of patch impedance required for matching.
- Performance of the designed, fabricated, tested, and patch compensated tandem coupler is found improved and the optimum performance is obtained without affecting the coupling. The final testing shows coupling of -3 ± 0.2 dB, output of -3 ± 0.2 dB, return loss of less than -32 dB, and isolation of better than -31 dB in the given frequency range of 91.2 ± 15 MHz. The same is found providing the return loss of -40 dB and isolation of -33 dB at the center frequency 91.2 MHz. Patch compensated prototype 3 ± 0.2 dB hybrid

coupler is indigenously developed and tested at 91.2 $\pm$ 15 MHz for 2.5 kW power handling capability.

- This prototype has successfully created the process for indigenous development of 2.5 kW, 3 dB hybrid coupler at any required frequency from 10 to 100 MHz. The concept, designing, and development procedure have imparted sufficient experience that will be useful while making 3 dB hybrid coupler of more than 100 kW power rating at the various frequencies within the range of 10–100 MHz, mainly for the ion cyclotron resonant heating systems of plasma in the tokamaks.

ACKNOWLEDGMENTS

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REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 014703 (2016)

Design of the 1.5 MW, 30-96 MHz ultra-wideband 3 dB high power hybrid coupler for Ion Cyclotron Resonance Frequency (ICRF) heating in fusion grade reactor

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Design and developmental procedure of strip-line based 1.5 MW, 30-96 MHz, ultra-wideband high power 3 dB hybrid coupler has been presented and its applicability in ion cyclotron resonance heating (ICRH) in tokamak is discussed. For the high power handling capability, spacing between conductors and ground need to very high. Hence other structural parameters like strip-width, strip thickness coupling gap, and junction also become large which can be gone upto optimum limit where various constrains like fabrication tolerance, discontinuities, and excitation of higher TE and TM modes become prominent and significantly deteriorates the desired parameters of the coupled lines system. In designed hybrid coupler, two 8.34 dB coupled lines are connected in tandem to get desired coupling of 3 dB and air is used as dielectric. The spacing between ground and conductors are taken as 0.164 m for 1.5 MW power handling capability. To have the desired spacing, each of 8.34 dB segments are designed with inner dimension of $3.6 \times 1.0 \times 40$ cm where constraints have been significantly realized, compensated, and applied in designing of 1.5 MW hybrid coupler and presented in paper. © *2016 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4939481]

I. INTRODUCTION

The broadband coupled lines are used in the development of many rf components such as power divider, combiner, balanced mixer, phase correlator, balanced amplifier, balanced modulator, attenuator, power measurements, and antenna array networks. The development of strip-line based 3 dB broadband hybrid coupler is one of its application. The 3 dB hybrid coupler can be used as power combiner/divider or to protect the rf source by coupling the reflected power with isolated port terminated with the dummy load.

The ICRH system of tokamak utilizes continuous wave radio frequency (cwrf) upto few MW at many frequencies in the range of 20-120 MHz. The frequency depends upon geometry of the tokamak, desired plasma parameters, and toroidal magnetic field at the center of tokamak vessel.[1] The ICRF generators are used to feed the rf power to the plasma with ICRH antennae. These should ideally be operated with matched load. The antennae load impedance not only depends on the antennae geometry but also on the boundary conditions of plasma which offer continuously variable mismatched load. Due to the mismatched loading, significant amount of the rf power is reflected back which may cause of inconsistent performance or damage to the generator.[2–5] The conventional matching systems operates at slower time scale and may fail to cope with the faster variation of plasma impedance. The 3 dB hybrid coupler is used to provide the essential protection to the rf generator from the reflected power.[6]

Schematic of the 3 dB hybrid coupler is shown in Fig. 1 in which rf power input at port-1 is equally divided into the output port-2 and coupled port-3 with phase difference of 90°, whereas port-4 is isolated. In ICRH system of the tokamak, port-2 and port-3 are connected with antennae terminated with plasma boundary inside tokamak and port-4 is match terminated with dummy load, whereas rf source is connect at port-1. In case port-2 and port-3 are identically mismatched the total reflected power isolated at dummy load through port-4. Thus, rf generator is protected from reflected power.[7–9]

Application of the hybrid coupler has been made in various ICRH systems of the tokamak for better efficiency, reliable operation and isolation of the reflected power from the rf generator.[10,11] However, the hybrid couplers that are developed for plasma ICRF heating are rated for narrow frequency band and are not able to cover full operational frequency band of the proposed ICRH experiments. Therefore, coupling network need to be altered with every change in operating frequency. For example, in steady state superconducting tokamak SST-1, a 3 dB hybrid coupler of 1.5 MW power handling capability is used to feed the rf power to plasma inside tokamak via two antennae. Coupler is procured in total five segments where specific numbers of segment are required to be arranged in particular manner for specified narrow operating frequencies range given as 22-25 MHz, 43-48 MHz, 65-75 MHz, and 87-97 MHz. To switch over from one to another given frequency range, device has to reassembled in specific manner. The assembling of such a bulky and dimension sensitive structure consumes time, manpower, and needs alteration in peripheral rigid coaxial transmission lines while changing the configuration. Moreover, ICRF heating experiments cannot be performed outside of the specified frequencies. In best of

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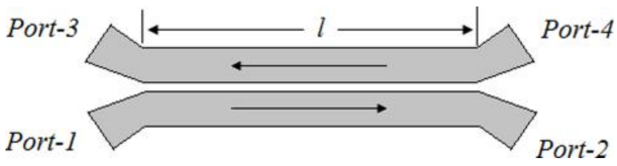

FIG. 1. Schematic of the 3 dB hybrid coupler.

our knowledge, development of ultra-wideband 3 dB hybrid coupler of 1.5 MW continuous wave high power handling capability is not yet reported. Therefore, initiative towards the development of ultra-wideband high power hybrid coupler for the ICRF heating of the tokamak has been carried out in many steps. The design, fabrication, and testing of the 3 dB hybrid couplers of 2 kW and 200 kW power handling capability for frequency range of 84–98 MHz (narrowband) and 38–116 MHz (ultra-wideband) are completed at intermediate stages and published earlier.[9,12,13,18] Stepwise brief discussion on earlier works along with current studies is presented as follow.

1. *A strip line based prototype 3 dB tandem hybrid coupler* of frequency 91.2 ± 15 MHz and 2.5 kW power handling capability has been developed in first step and presented in earlier study.[9] To achieve the wider coupling gap for the high power handling capability, two 8.34 dB TEM broadside coupled strip-line sections in tandem are connected to have 3 dB coupling. Air as dielectric is used to minimize the insertion and other losses which renders the up-gradation from prototype to high power application easier. Later on, performance of the developed model has been optimised using novel theoretical approach known as patch compensation technique.[9] The developed hybrid coupler is successfully tested and creates the process for indigenous development at any frequency in the range of HF and VHF. Photograph of the fabricated hybrid coupler is shown in Fig. 2. The fabricated hybrid coupler is tested and found providing return loss of 40 dB and isolation of 33 dB at the center frequency 91.2 MHz.
2. *Development of* 200 kW *ultra-wideband multi-element lines* has been successfully completed in this step and presented in earlier studies.[12,13] The multi-octave bandwidth can be achieved by means of cascading several quarter-wavelength elements called multi-element coupled lines. The theory of multi-element coupled lines is presented as earlier[14–17] where coupled elements are proposed to be cascaded in a certain configuration to achieve the desired coupling and frequency bandwidth. These theories hold good and yields ideal performance for multi-element coupled lines design. In a practical design, junctions are employed for the joining of two different coupled elements which produce the undesirable reactive effect abbreviated as junction discontinuity effect(JDE). This effect deteriorates the performances of multi-element coupled lines from the theoretical prediction. The quantum of the effect is mainly depends on required junction length for given size of the coupled lines. However, the existing theory does not take into consideration of unavoidable junction discontinuity effect. To prevent the rf breakdown, conductor to conductor and conductor to ground spacings are taken to be very high. Therefore, structural parameters like strip-width, strip thickness and coupling gap also become large and in the same ratio size of junction also become large. JDE depends on length and impedance of the junction become more prominent in the high power coupled lines for HF and VHF applications. The JDE has been comprehensively studied, analysed and a theory *viz.* modified theory is developed for compensation of it. The developed theory is applied in designing of the 8.34 ± 0.2 dB coupled section consisting of 3-cascaded elements as shown in Fig. 3. The rectangular strip-line central conductors are arranged in particular configuration and placed in the grounded metallic enclosure. Each of the quarter wavelength coupled lines are designed for 75 MHz and cascaded in symmetrical manner with junctions of length $l = \lambda/20$. The designed section is simulated using HFSS which considers the all practical dimension including junctions. In simulation results, performances are significantly found deteriorated from the theoretical ones.[14] The problem has been investigated and found associated with JDE.

   For the compensation of JDE, Modified theory has been applied in designing of 8.34 ± 0.2 dB section. After incorporating the modified theory section is simulated using HFSS where simulation results are found in agreement with earlier Cristal theory.[14] This highlight significance of the modified theory in multi-element coupled lines development.
3. *Design and fabrication of* 200 kW*, (38-116) MHz, ultra-wideband 3 dB hybrid coupler* has been completed and tested for the desired performance and presented in earlier study.[18] The previous experience of designing

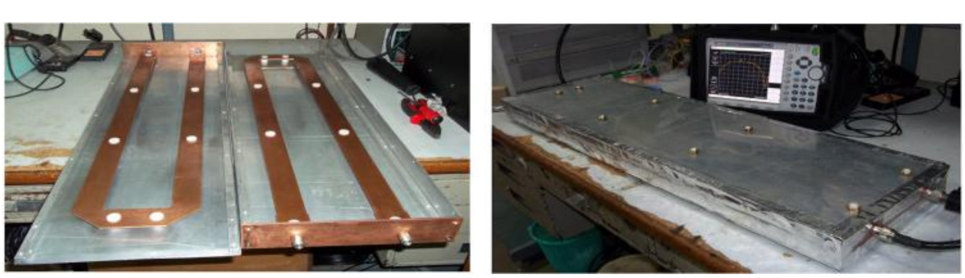

FIG. 2. Photograph of the inner assembly of the fabricated 2 kW, 3 dB tandem hybrid coupler.

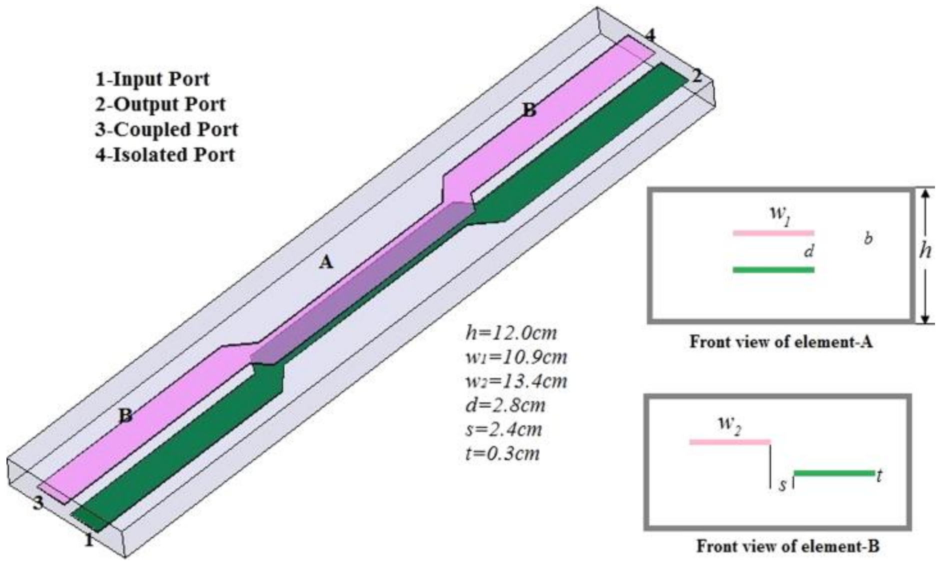

FIG. 3. The 3-D model of 3-elements (namely, A, B, C), 8.34 dB coupled lines section used in simulation.

of high power multi-element coupled line is utilized in development of 3-elements, 8.34 dB coupled lines section and a tandem 3 dB hybrid coupler has been fabricated using two 8.34 dB coupled lines. Photograph of the fabricated coupler is shown in Fig. 4. The fabricated hybrid coupler is tested and found providing return loss and isolation better than 25 dB. The fabricated 3 dB hybrid coupler can directly be utilized in ICRH system of the medium size tokamak.

- *Design of the 1.5 MW 30-96 MHz ultra-wideband 3 dB hybrid coupler* has been completed and presented in paper first time. The peak power handling capability is limited by high voltage breakdown strength that is mainly depend on the applicable power, frequency, and structural geometry of the device.[20] To reduce the insertion loss, in high power continuous wave rf system air is used as dielectric where low dielectric constant insulators are used to hold the inner conductor inside the outer conductor box. At the atmospheric temperature and pressure the breakdown strength of dry air is approximately 30.0 kV/cm.[19] The value of the rated breakdown strength can be lowered as frequency increases. Moreover, discontinuity like sharp edges and corners in the geometry also introduce the unwanted reactive effect. Therefore, resulting breakdown may occur at lower than the rated value. The combined effect of these factors is very unpredicted. Therefore, for the safety purpose, conductor to conductor and conductor gaps are taken four times of theoretical one. For the high power handling capability required spacing between conductors and ground must be high. Hence, other structural parameters like strip-width, strip thickness, and coupling gap also become large. Thus, coupled lines cross section become larger and result oversize system. The maximum permissible spacing is governed by the onset of TE and TM modes.[22] To restrict the lowest order TE modes, average circumferential distance of coupled cross section must not exceed about one wavelength. The mode conversion from TEM to TE or TM modes represents a source of power loss and resulting deterioration in coupling, output, return loss, and isolation characteristic. Thus, permissible limit of the gaps is restricted hence the power handling capability. Here, our objective to develop the 1.5 MW hybrid coupler without causing any effect of constraints on desired performances. Moreover, for the compensation of junction discontinuity effect, modified theory is applied. In designed 1.5 MW hybrid coupler, two 8.34 dB coupled lines are connected in tandem to get desired coupling of 3 dB and air is used as dielectric. The spacing between ground and conductors is taken as 0.40 m for 1.5 MW power handling capability. To have the desired spacings, each of 8.34 dB segments are designed with inner dimension of $3.6 \times 1.0 \times 40$ cm. In such a bigger size of the coupled section discussed constraints are significantly realized, compensated, and applied in designing.

FIG. 4. Photograph of the inner one side assembly of the fabricated 200 kW, (38-116) MHz, tandem 3 dB hybrid coupler.

Section II explains the concept and theory of multi-element coupled lines in ultra-high power application. The conceptual design and simulation of the designed 1.5 MW hybrid coupler are described in Section III. The assembly drawings are illustrated in Section IV and simulation results are discussed in Section V. Finally, the conclusion is presented in Section VI.

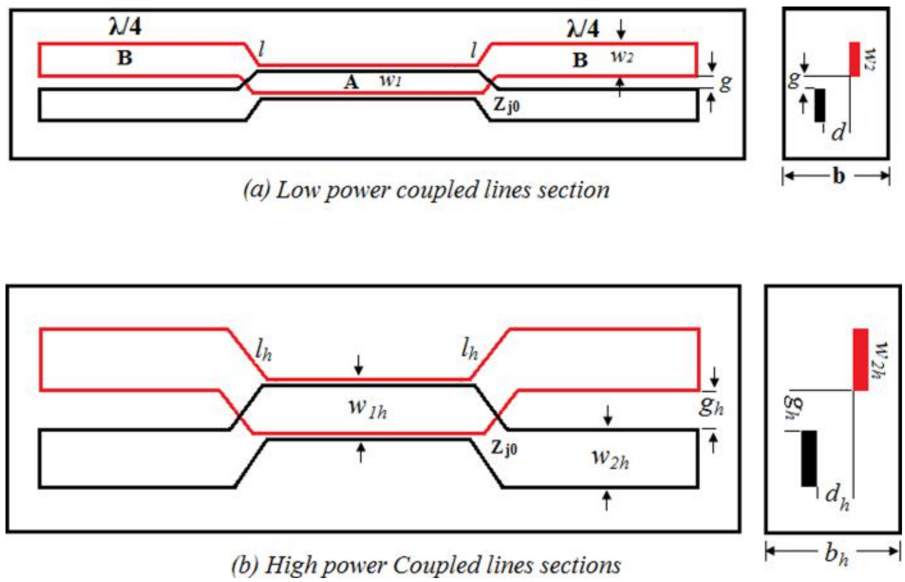

FIG. 5. Schematic of the (a) top and side view of low power, (b) top and side view for high power multi-element coupled lines.

II. MULTI-ELEMENT COUPLED LINES IN ULTRA-HIGH POWER APPLICATION

In multi-element coupled lines numbers coupled elements are cascaded in specific manner to have wider bandwidth where each coupled element having length of $\lambda/4$ at center frequency. The bandwidth increases with increase the number of elements.[14] The development of broadband multi-element coupled lines of MW power rating is very challenging due to the various constraints as discussed and therefore, work has been carried out in many steps. Design and development of the multi-element coupled lines based, 200 kW, (38-116) MHz, ultra-wideband continuous wave (cw) 3 dB hybrid coupler has been presented as earlier.[12,13] The earlier experience is utilized in of designing of 1.5 MW hybrid coupler. Here, design and developmental procedure of strip-line based 1.5 MW, 30-96 MHz, ultra-wideband high power 3 dB hybrid coupler has been presented. The structural change in coupled lines section with power handling capability can be clarified with the aid of Fig. 5 where subsections (a) and (b) represents the schematic of 3-elements 8.34 dB coupled line section at low and high power, respectively. Here, one can observed that as the power handling capability increase required spacing between conductors and ground must be high. Hence other structural parameters like strip-width, strip thickness coupling gap, and junction also become large which can be gone upto optimum limit where various constrains like fabrication tolerance, discontinuities, and excitation of higher TE and TM modes become prominent and significantly deteriorates the desired parameters of the coupled lines system. The constraints other than TE and TM mode have been already realised, compensated, and tested in earlier steps as presented.[9,12,13,18] Here, excitation of TE and TM modes is comprehensively is investigated first time in designing of 1.5 MW, 3-elements, 8.34 ± 0.2 dB coupled line system and presented in paper.

In large size system, excitation higher of modes, TE and TM are the quite significant as the conductor size increases beyond the certain limit. This has to be compensated because mode conversion from TEM to TE or TM modes represents a source of power loss which degrade coupling, output, return loss, and isolation the performances of the coupled section.

The lowest order TE mode can propagate when the spacing b, d and strip-width w are such that the average circumferential distance as indicated with dotted line in Fig. 6 exceeds beyond one wavelength. Excitation of TM is not found in case the strip-line of impedance $Z_0 \le 120\ \Omega$ and ($w/b \ge 0.215$) in HF and VHF ranges. Here, coupled lines are designed with 100 Ω impedance hence only excitation TE mode is taken into the account. The cutoff wavelength of TE mode, λ_{ce} can be expressed in terms of strip-line parameters as[22]

$$\begin{aligned}\lambda_{ce(A)} &= \sqrt{\epsilon_r}\,[2w_1 + 2\pi(d+2t)]\,,\\ \lambda_{ce(B)} &= \sqrt{\epsilon_r}\,[4w_2 + 2g + 2\pi(d+2t)]\,.\end{aligned} \tag{1}$$

Thus, TE mode cutoff frequency for element-A, $f_{c(A)}$ and element-B, $f_{c(B)}$ can be expressed as

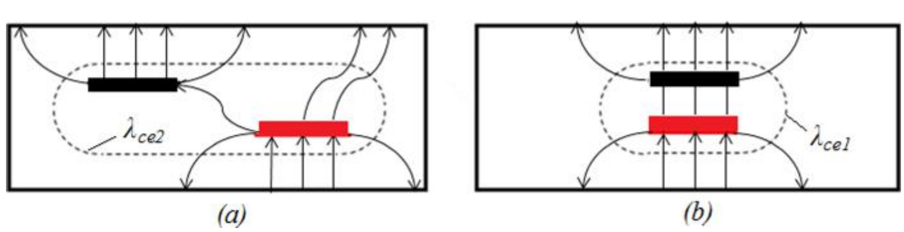

FIG. 6. Electric field lines for lowest TE modes in (a) Element-B and (b) Element-A.

$$f_{c(A)} = \frac{c}{\lambda_{ce(A)}} = \frac{c}{\sqrt{\epsilon_r}\,[2w_1 + 2\pi(d+2t)]},$$
$$f_{c(B)} = \frac{c}{\lambda_{ce(B)}} = \frac{c}{\sqrt{\epsilon_r}\,[4w_2 + 2g + 2\pi(d+2t)]}. \tag{2}$$

For example, as presented in earlier work[18] developed 200 kW hybrid coupler has been fabricated with following dimension:

$$w_1 = 0.109 \text{ m},\quad w_2 = 0.132 \text{ m},\quad d = 0.04 \text{ m}$$
$$t = 0.003 \text{ m},\quad g = 0.0172 \text{ m},\quad \epsilon_r = 1.$$

Substituting these parameters in Eq. (2) we get

$$f_{c(A)} = \frac{3\times10^8}{[2\times0.109 + 2\times3.14\times0.046]} = 1.25 \text{ GHz},$$
$$f_{c(B)} = \frac{3\times10^8}{[4\times0.132 + 2\times0.0172 + 2\times3.14\times0.046]} = 348 \text{ MHz}. \tag{3}$$

It can be seen that the cutoff frequency for the TE mode in element-A is 1.25 GHz and in element-B is 348 MHz. That means, TE mode can propagate above 384 MHz in 8.34 ± 0.2 dB coupled lines section which consist of element-A and element-B. Therefore, the fabricated device can operate in the frequency range of 40-110 MHz without excitation of higher modes. Thus, it can safely be used without any deterioration in the results in prescribed frequency band.

To restrict the electric field within the 1.0 MV/m for the 1.5 MW power handling capability outer conductors spacing of 0.40 m is calculated and, respectively, all other strip-line dimension are also calculated as

$$w_{1h} = 0.39 \text{ m},\quad w_{2h} = 0.56 \text{ m},\quad d_h = 0.153 \text{ m}$$
$$t_h = 0.005,\quad g_h = 0.205 \text{ m},\quad \epsilon_r = 1$$

Using Eq. (2), cutoff frequency for element-A, $f_{hc(A)}$ and element-B, $f_{hc(B)}$ are calculated as

$$f_{hc(A)} = 166 \text{ MHz},\qquad f_{hc(B)} = 80 \text{ MHz}. \tag{4}$$

From the above it can be analysed that above 80 MHz higher mode TE can be excited in the 8.34 ± 0.2 dB coupled lines section. Thus, required spacing of 0.40 m and other resulting of coupled strip-line is not permissible due to the excitation of TE mode. Therefore, 1.5 MW power handling capability cannot be achieved in this design. It can also be noticed that application of such a large dimension of strip-line conductor in HF and VHF frequency range is difficult due to following reasons.

- Large dimension of the coupled lines create the structural configuration conflict between element-A and element-B and junction discontinuity effect become more prominent.
- To maintain the specified gaps between the bulky copper inner coupled strip-lines over the required length is very difficult and small deviation from specified structural dimension induces huge deterioration in performance.

III. CONCEPT, DESIGN, AND SIMULATION OF THE 1.5 MW 3 DB HYBRID COUPLER

For 1.5 MW power handling capability, required spacing cannot be achieved in earlier configuration due to possibility of the excitation of the TE modes as discussed in Sec. II. Without modifying the spacing, strip-line width can be reduced by increasing the characteristic of line impedance. Therefore, idea is to use the two 100 Ω, 3 dB tandem hybrid coupler to get 50 Ω overall. In this way, strip-width can be reduced with ratio of 4 approximately as compared to 50 Ω, 3 dB hybrid coupler without affecting the ground spacing. Schematic of the proposed configuration of 1.5 MW, 3 dB hybrid coupler is shown in Fig. 7 where two identical section can be observed. In each section, two identical stepped rectangles (presented by dark and light ones) of strip-line overlaps one another which represent the 100 Ω 3 dB hybrid coupler. The stepping

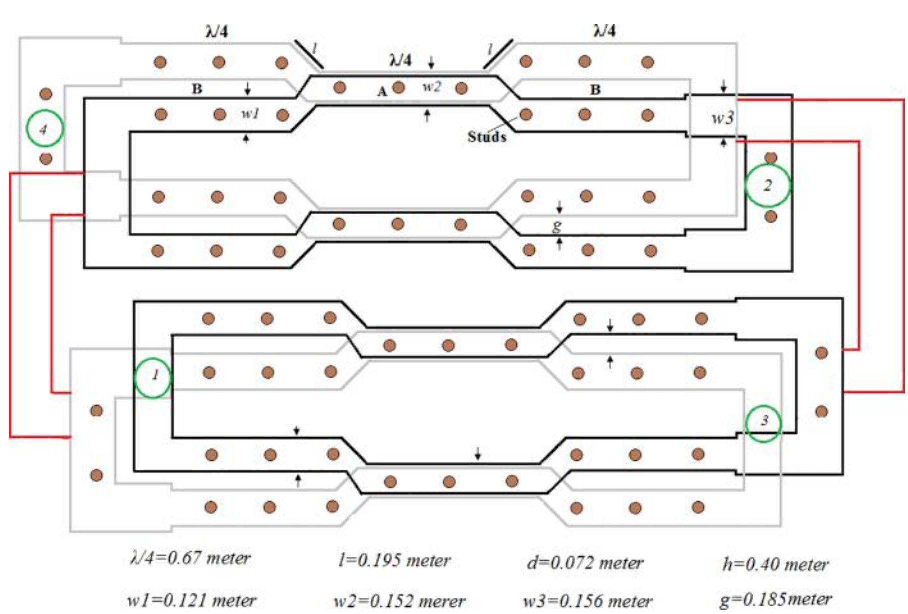

FIG. 7. Schematic of 1.5 MW, 3 dB hybrid coupler.

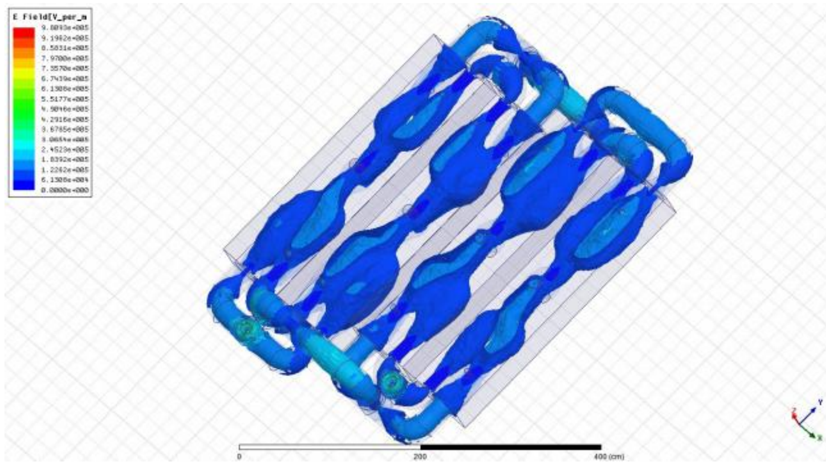

FIG. 8. Electric field plot.

in rectangle of strip-line is made in such a way that each section forms two 3-element, 8.34 ± 0.2 coupled lines sections connected in tandem to get 3 dB of coupling. Both of the sections are connected in parallel using connecting line to provide the 50 Ω overall. The structural design parameters for element-A, element-B, and connecting lines of 1.5 MW hybrid coupler as shown in Fig. 7 can be calculated using known equations.[9,21,22] Design parameters are given as

$$w_1 = 0.121\text{ m},\quad w_2 = 0.152\text{ m},\quad d = 0.072\text{ m}$$
$$t = 0.005\text{ m},\quad g = 0.1851\text{ m},\quad \epsilon_r = 1.$$

Using these dimension $f_{c(A)}$ and $f_{c(B)}$ are calculated as,

$$f_{c(A)} = 396\text{ MHz},\qquad f_{c(B)} = 200\text{ MHz}. \tag{5}$$

From the above it can be observed that designed hybrid coupler can work in the required frequency range of 30-96 MHz without excitation of higher TE modes. The inner strip-line dimensions are also reduced with ratio of 4 and it is found optimized. Therefore, other problem associated to the bigger size of the inner strip-line is also alleviated. The resulting model using these structural parameters is simulated using HFSS software and the electric field plot is shown in Fig. 8.

At 1.5 MW input maximum electric field is found below 1.0 MV/m, i.e., in safe limit. Thus, the designed hybrid coupler is verified for the 1.5 MW power handling capability using electromagnetic simulation.

IV. ASSEMBLY DRAWING OF THE HYBRID COUPLER

Assembly drawing of the designed hybrid coupler is shown in Fig. 9 where two identical 100 Ω hybrid couplers are arranged at one above other and connected with $9\frac{3}{16}$ in., 100 Ω transmission lines in parallel. The equivalent of the connection provides the standard characteristic impedance of 50 Ω overall. Each of the rectangular box have inner space of 3.40 m × 1.0 m × 0.4 m and designed to fabricate with aluminium sheet of 5 mm thickness. Total space used by the device is approximately 5.0 m × 2.5 m × 2.0 m. Each rectangular box contains two 8.34 ± 0.2 dB coupled lines connected in tandem.

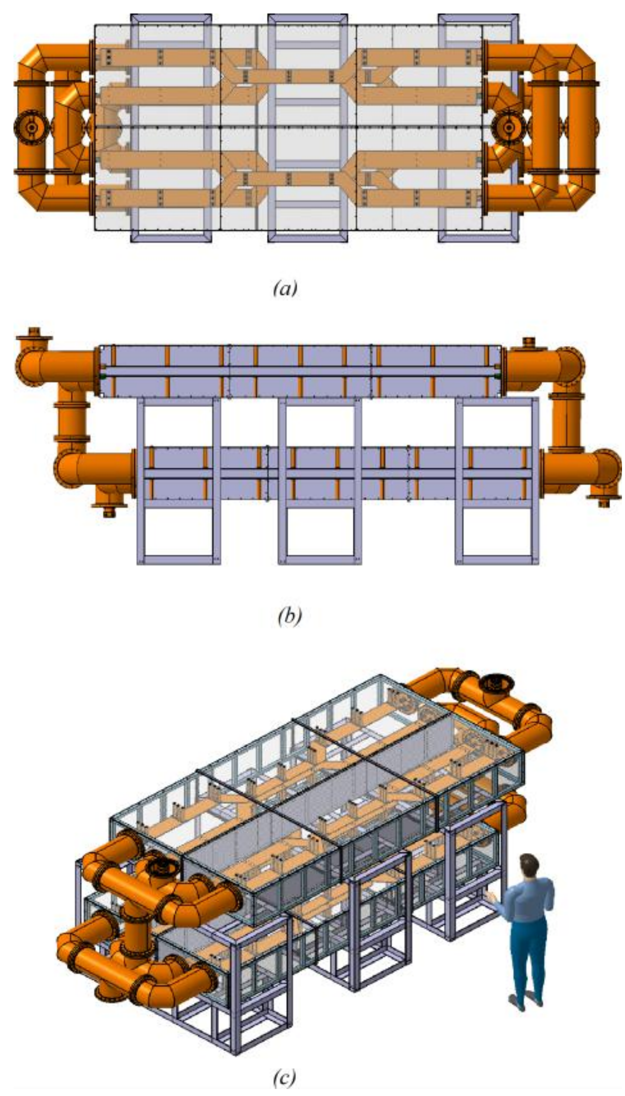

FIG. 9. Assembly drawing of the designed 1.5 MW 3 dB hybrid coupler. (a) Top view. (b) Side view. (c) Super view.

Each section of the coupled lines has two stepped 5 mm thick copper strip-line conductors that are overlapped on each other in symmetrical manner. Perspex holders are used to hold the strip-line conductor inside the outer conductor box. The

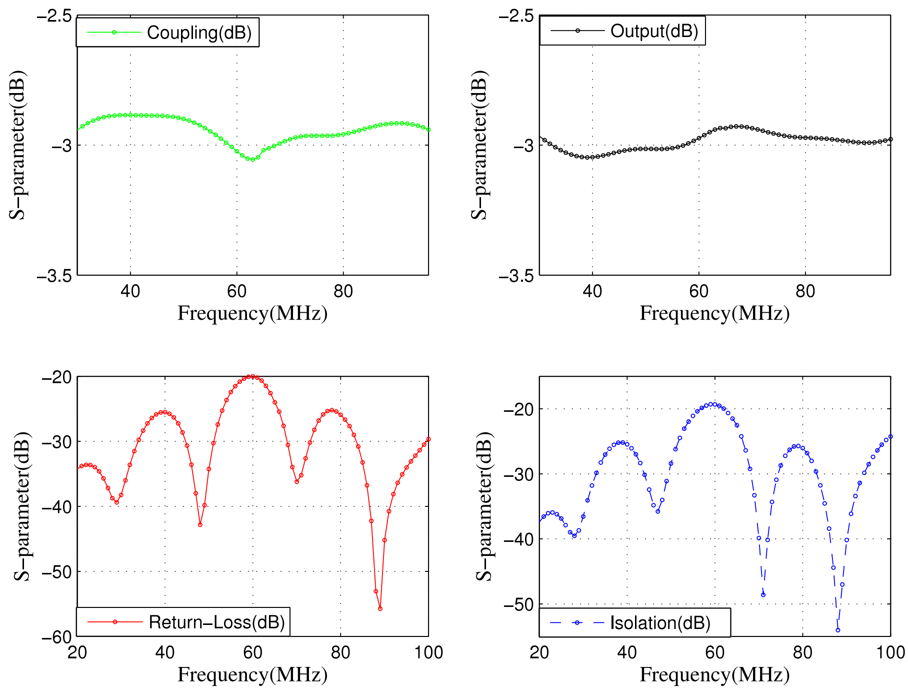

FIG. 10. Simulation results.

100 Ω coaxial transmission lines are used to connect two 8.34 ± 0.2 dB coupled lines sections. The detailed dimension of the inner strip-line are shown in Fig. 7. All of the four ports are made to provide $9\frac{3}{16}$ in., 50 Ω coaxial transmission line as the standard termination is required.

V. RESULT AND DISCUSSION

A 1.5 MW, 3 ± 0.2 dB tandem hybrid coupler has been designed for the ultra-wideband of 30–96 MHz. To achieve the required spacing for 1.5 MW power handling capability two 100 Ω hybrid couplers are connected in parallel. The designed model is simulated with HFSS software. Simulation results as shown in Fig. 10 are found providing coupling of -3 ± 0.25 dB, output of -3 ± 0.25 dB, return loss, and isolation better than 20 dB within specified frequency range of 30-90 MHz. The maximum electric field on the structure is found below 1.0 MV/m. Thus, power handling capability is verified for 1.5 MW and results are also found as per application requirements.

Power handling capability of the coupled strip-line is mainly depends on various losses and the peak value of electric field at strip conductor. Proposed Hybrid coupler uses air as dielectric. Breakdown strength of the air dielectric is defined as 3×10^4 V_{dc}/cm for dc or 1.4710^4 $V_{rf}(peak)$/cm for rf,[9] which means $(1.47) \times 10^4$ V_{rf}/cm or 1.47 MV/m can apply between two strip-line are placed 1.0 cm away from each other in air without causing breakdown. To limit the maximum electric field below the specified value of 1.47 MV/m, outer box is designed with 40 cm height. Other dimension mainly depend on outer box height and desired parameters. By having the 40 cm of box height, maximum electric field on the structure is found below 1.0 MV/m in simulation results. Hence, power handling capability of the hybrid coupler is verified for 1.5 MW.

VI. CONCLUSION

Design, simulation, and assembly drawing of the ultra-wideband, 1.5 MW 3 dB hybrid coupler in frequency range of 30-96 MHz are presented. At the desired power handling capability and frequency range, a major concern is that the size of the device becomes very large which is approximately 5 m in length, 2.5 m in width and 2 m in height. The problem of higher modes and discontinuities that are mainly associated due to the larger dimension of the device have been studied, compensated, and incorporated in design. Moreover, optimization of such a large device at this frequency range for the desired performances is very challenging. The earlier experience has been utilized in optimization of the design parameter to get desired performance. The foundation of the proposed 1.5 MW hybrid coupler is made on the basis of earlier studies[18] where fabrication and testing of 200 kW, ultra-wideband hybrid coupler are presented for the desired performance. For the easier fabrication, structural configuration of the device is taken as similar to the fabricated 200 kW, (38-116) MHz, ultra-wideband 3 dB hybrid coupler presented as earlier.[18] Therefore, brief of the previous works[9,12,13,18] is also discussed in Sec. I. Designed 3 dB hybrid coupler is simulated using software HFSS where the results are found in agreement to the desired values. As per previous experiences it can be expected that device will also provide very acceptable results after fabrication. Fabrication of the proposed 3 dB hybrid coupler is already in process. After fabrication this can be directly utilized in ICRH system of tokamak like SST-1, ITER, Tore supra, etc.

Design, Fabrication and Testing of Pressurized Co-axial Directional Coupler for High RF Power Measurements for SST-1 ICRH System

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Abstract — **Directional couplers are used to monitor forward and reflected high RF powers. At Mega Hertz range of frequencies, normally loop type directional couplers are used. The loop samples electric or magnetic fields. The penetration and orientation of the loops are adjusted in such a way that the magnitude of electric and magnetic current is same in the two arms of the loop. In this configuration one arm of the loop shows incident power while the other arm gives reflected power. Secondary arm is terminated into 50 ohm in order to avoid multiple reflections. The rectangular coupling loop used in the developed directional coupler is having the dimensions of 46 mm x 19.5 mm (W X H). It is made up of copper. The directional coupler developed can be pressurized up to 3.0 bar absolute pressure. A specific Teflon cup design is used to pressurize the directional coupler. The size of the directional coupler is 6 1/8" EIA standard. The inner and outer conductors are made from 99.5% ETP copper. Flanges are made from 60:40 electronic grade brass. Inner conductor joints are of brass with silver-plating. The return loss obtained is better than 30 dB. The coupling factor is variable from 40 dB to 57 dB depending upon probe penetration.**

The coaxial directional coupler has been designed, fabricated and tested indigenously at IPR.

Here we present the details of design, fabrication and test results at various frequencies of operation.

Index Term — **Coupling factor, directional coupler, loops, RF power, teflon cup.**

I. Introduction

Now it is well accepted that high power RF heating of plasma in the range of ion cyclotron frequencies is required for fusion reactors to get the required temperature of 40 KeV and more for starting the fusion reaction. The required frequency lies in the range of 10 to 100 MHz and the required RF power is around 50-70 MW. In order to have maximum power transfer, one needs to do on-line matching of the antenna impedance with continuously variable plasma impedance. For this purpose one needs to measure forward and reflected power in the transmission line and one needs to do on-line calculations to adjust the matching devices. Directional coupler (DC) plays an important role in measuring high RF power without disturbing the flow of power in the transmission line.

Coaxial directional Couplers are passive devices used to monitor forward and reflected RF powers in transmission line without making the direct connection to the transmission line carrying the power.

We have designed, fabricated and tested an inline pressurized directional coupler developed indigenously at IPR.

II. Principal Of Operation

At MHz range, loop type directional couplers are used. The loop samples electric or magnetic fields. The penetration and orientations are adjusted in such a way that the magnitude of electric and magnetic current is same in the two arms of the loop. In this configuration one arm of the loop shows incident power while the other arm gives reflected power. Secondary arm is terminated into 50 ohm in order to avoid multiple reflections.

III. RF Design Criteria

The size of the directional coupler is 6 1/8" EIA standard. The dimensions are selected to get characteristic impedance of 50 ohm. Surface finish of 2 delta has been maintained for the inner surface of outer conductor and outer surface of inner conductor to avoid rf breakdown due to sharp edges. Inner conductor joints are of brass with silver-plating for better electrical contacts. DC is tested for pressurization upto 3 bar (dry N_2 gas) absolute pressure to handle high RF power and to get higher breakdown strength.

The ratio of the outer diameter (a) of the pipe to the diameter (b) of the inner conductor, as well as the ratios of the diameters of the pins (connected to rectangular loop) to the various connectors and the diameters of the holes must satisfy the usual impedance (Zo) relation for an air-spaced coaxial line:

Zo= 138 log (a/b) (1)

In our case, b= 66.0 mm and a = 151.9 mm of main line, therefore Zo= 50 ohm.

IV. Mechanical Details Of The Developed Directional Coupler

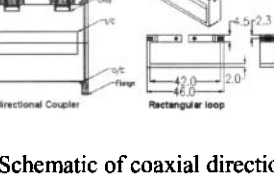

Fig. 1. Schematic of coaxial directional coupler.

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The schematic of the DC has been shown in Fig 1. The inner diameter of the outer conductor is 151.9 mm and outer diameter of inner conductor is 66 mm. Surface finish of 2 deltas has been maintained for the inner surface of outer conductor and outer surface of inner conductor. It is connected to Vector Network Analyzer (VNA) with the help of 6" to 3" coaxial step reducer for testing purpose. The total length of DC is 300 mm.

It has two ports - one for forward and another for reflected power measurements.

The ports contain rectangular coupling loop having the dimensions of 46 mm x 10 mm (W X H). It is made up of copper. The directional coupler can be pressurized up to 3.0 bar. A specific Teflon cup design is used to pressurize the directional coupler. The size of the directional coupler is 6 1/8" EIA standard. The inner and outer conductors are made from 99.5% ETP copper. Flanges are made from 60:40 electronic grade brass. Inner conductor joints are of brass.

The moving arrangement has been attached for adjusting the orientation and penetration of the probes with measuring scales. A photograph of developed coaxial directional coupler is shown in Fig 2.

Fig. 2. Photograph of coaxial directional coupler.

V. TEST SETUP

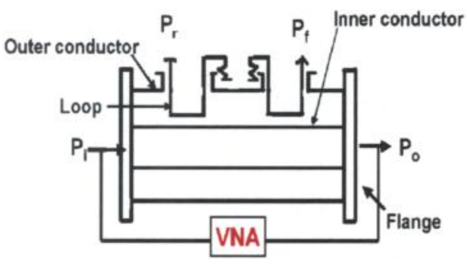

Fig. 3. Schematic of test setup for low power RF testing of coaxial directional coupler.

The Low power rf test setup for the coaxial directional coupler measurement is shown in Fig 3. Here P_i denotes the input port, P_o denotes the output port, P_f denotes the forward coupling port and P_r denotes the reverse coupling port. Two-port measurement has been done using VNA for measuring the S-parameter of main line as well as forward and reverse coupling from the coupling ports.

It has two measuring ports – one for forward power measurement and another for reflected power measurement. Each port is having two outputs from two arm of rectangular loop. The two ports may be treated as independent. Each port is having one loop to couple electric or magnetic field.

The loop samples electric or magnetic fields. The penetration and orientation are adjusted in such a way that the magnitude of the currents generated by electric or magnetic fields is same in the primary arms of the loop. In this configuration the primary arms of the loop (in first port) shows incident power while the secondary arms are terminated into 50 ohm in order to avoid multiple reflections.

The second port is used for the reflected power measurement using same method as in the first port.

V. RESULT AND DISCUSSION

The test setup has been made for measuring the forward and reverse coupling parameters. Vector Network Analyzer has been used for measuring S-parameters. Low power rf has been fed using one port of VNA to input of directional coupler, output of directional coupler has been connected to different values of load and other port of VNA is used for measuring the coupling parameters.

It has been observed that the forward coupling remains almost constant at different load (2 Ω, 5 Ω, 10 Ω etc) values, which is expected because forward coupling should remain constant irrespective of load, hence improves the measurement accuracy. It is primary requirement of any directional coupler to have constant forward coupling over different load values.

Fig.4 shows the variation of return loss Vs forward coupling at 13.56 MHz.

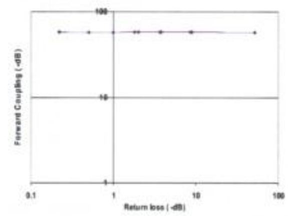

Fig. 4. Variation of return loss V/s forward coupling at 13.56 MHz

The reverse coupling is minimum when matched load (50 Ω) is connected therefore minimum interference with forward coupling which improves the measurement accuracy (See Fig.5).

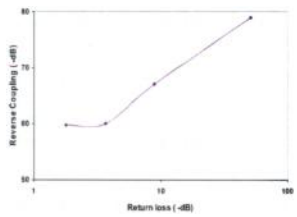

Fig. 5. Variation of return loss Vs reverse coupling at 13.56 MHz

The VSWR (voltage standing wave ratio) is near to 1 when load is 50 Ω, which is important to minimize mismatch errors and to improve measurement accuracy (See Fig.6).

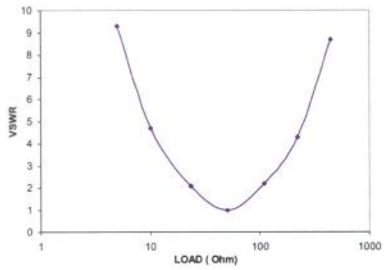

Fig. 6. Variation of return loss Vs reverse coupling at 13.56 MHz

The reflection coefficient varies from –1 to +1 at different load values (i.e. short to open) and matches with the calculated values (See Fig.7).

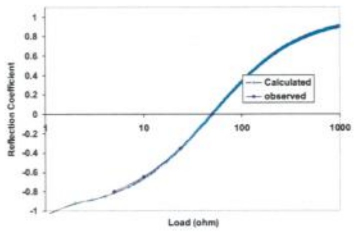

Fig. 7. Variation of load Vs reflection coefficient

The ratio of forward and reverse coupling remain almost constant at different frequencies, which shows that the directional coupler can be used for wide band of frequencies (See Fig.8).

The return loss is less than –40 dB for frequency range 10-100 MHz which is quite good as per transmission line design aspect (See Fig.9).

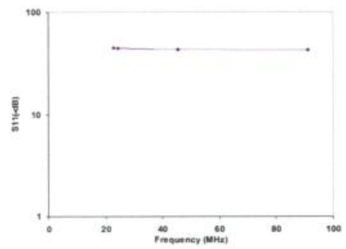

Fig. 8. Variation of forward and reverse coupling Vs frequency with 50 ohm.

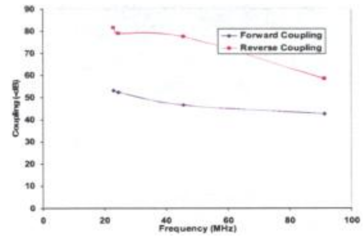

Fig.9. Variation of return loss Vs frequency with 50-ohm load

VII. Conclusion

The monolithic GaAs two-bit phase shifter (90°& 180°) have designed and realized. The two-bit phase shifter has designed using switch-network phase shifter topology. By switching between the phase shifting element of low pass and high pass filter, a constant phase shift has produced and this phase shift has relatively flat phase shift versus frequency characteristics. The main advantage of switch network phase shifter is compact in size, minimum phase variation and work over large bandwidth. This phase shifter has used in Phase array Radar Antenna applications.

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