Telecommunications and Radio Engineering, 77(15):1365-1374 (2018)

NOVEL COAXIAL CABLE IMPLEMENTATION OF MINIATURIZED WILKINSON POWER DIVIDER AND QUADRATURE HYBRID COUPLER FOR VHF APPLICATIONS

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In this article, novel implementations of Wilkinson Power Divider (WPD) and Quadrature (90^0) Hybrid Coupler (QHC) have been proposed using series and parallel combination of coaxial cables for Very High Frequency (VHF) applications. The proposed method of implementation using coaxial cables is advantageous in terms of its simplicity and it can work at higher power levels with proper choice of cables. Moreover, the fine tuning of the designed frequency for the proposed devices can be easily possible by merely trimming the cable length which is not easy with microstrip lines once its PCB fabrication is done. In addition, due to the use of flexible coaxial cables, there is good scope for miniaturization of the respective device. The proposed WPD and QHC show good matching at all the ports and very good amplitude balance, relative phase difference and isolation between the output ports. The proposed WPD and QHC show overall favorable performance fractional bandwidth respectively of 35.76% and 11.15%. In addition, the reduction in the lengths of the quarter wavelength transmission line sections of WPD is upto 55% and an overall size reduction of 23.50% has been achieved in QHC as compared to that of their respective conventional microstrip line designs, with potential for further miniaturization.

KEY WORDS*: coaxial cable, coupler, miniaturization, quadrature hybrid, VHF, Wilkinson power divider*

1. INTRODUCTION

Wilkinson power divider (WPD) is one of extensively used very high frequency (VHF) devices in feeding network for an antenna array and the power splitting/combining networks for amplifier modules. In many of the RF wireless telecommunication systems Quadrature (90^0) Hybrid Couplers (QHC) plays a role of fundamental building block in balanced mixers, frequency discriminators, modulators and power amplifiers. The major drawback of the conventional WPD and QHC is larger occupied areas due to the adoption of quarter-wavelength transmission line sections. For VHF band (30 MHz to 300 MHz) the required length of the transmission line is in meters which increases overall device size and limits its applications. In modern telecommunication due to system miniaturization and large scale integration, size-reduction is certainly desirable for each system component.

In the equal power split (3 dB) WPD the input power is equally divided into two output ports [1] and its equivalent transmission line circuit is as shown in Fig. 1 [2]. Many researchers have proposed several techniques to reduce the overall size of the power divider as well as to meet the price competitiveness for users [3-5]. In [3] parallel coupled line with defected ground structure, composite right-/left handed (CRLH) transmission line [4], and defected ground structure (DGS) [5] are used for miniaturization of power divider. The major drawback of DGS and CRLH line based on resonant type is back radiation which affects the operation of other microwave components and these structures need additional etching technique in fabrication process [6]. The electromagnetic band-gap (EBG) structures [7-8] are also used for miniaturization of power divider but it suffers with the design complexity.

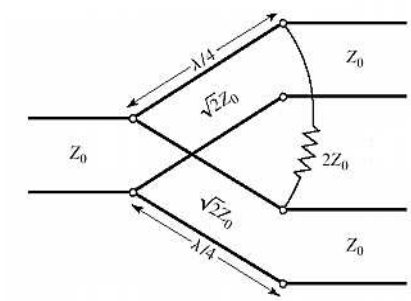

FIG. 1: Equivalent circuit of WPD

The QHC has a high degree of symmetry, as any port can be used as the input port. As shown in the Fig. 2, the output ports will always be on the opposite side of the junction from the input port, and the isolated port will be the remaining port on the same side as the input port [2]. Referring to Fig. 2, Z_{01} and Z_{02} are characteristic impedances of two transmission lines and Z_0 is the characteristic impedance of the transmission line at each port. The length of each transmission line of impedance Z_{01} and Z_{02} is one fourth of the guide wavelength (i.e., $\lambda_g/4$) at the design frequency. The signal applied to port 1 splits equally between ports 2 and 3 with one of the outputs

exhibiting a relative 90° phase shift. If ports 2 and 3 are properly terminated into matching impedances, nearly all the signal applied to port 1 is transmitted to the loads connected to ports 2 and 3. In this circumstance, port 4 receives negligible power and is termed 'isolated port'.

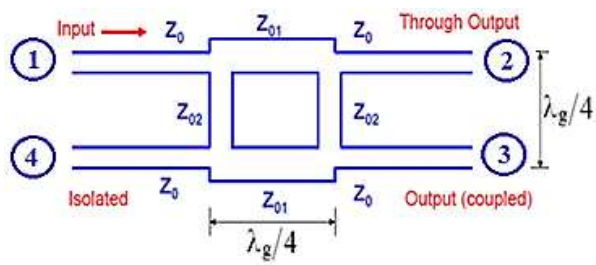

FIG.2: Block diagram of QHC

Reference work on hybrid couplers for the meter waves is largely unavailable in public domain [9]. In [9] a VHF QHC has been designed suspended stripline coupler, using two overlapping brass strips placed on the top and bottom surface of a Teflon substrate and it is not easy in terms of fabrication, and also bulky due to the use of heavy Teflon sheet. Miniaturized microstrip line based QHC, has been reported using defected ground structure (DGS) [10], meander shaped complementary single split ring resonator (CSSRR) [11], high-low impedance lines cascaded in meander line configuration [12]. Even though these slow wave structures used in [10-12] show good miniaturization, but there is a need of etching on both sides of the substrate, which requires additional position calibration and a minimum space underneath for proper functioning of slots, resulting in an increase in the circuit volume [13].

Thus, to implement a compact QHC for VHF band using microstrip lines as reported in [10-12] or using stripline as in [9], requires larger printed circuit board (PCB) and leads to higher cost. Subsequently, this limits its applications in portable VHF band like in Radar and in other wireless telecommunication systems. Also, the fine tuning of the center frequency is not easy once the PCB fabrication is done based on microstrip lines / stripline for a specific design frequency.

To make the coupler more compact, by following the quasi-lumped elements approach, QHC size is reduced by 71% [14]. In [15], the design of high power, low loss QHC for VHF (at 53 MHz) using lumped element has been reported. But as shown in [15], lumped element couplers have lesser bandwidth (7.5%) as compared to distributed element couplers. Also, commercially available lumped elements have limited choice of the available values.

The series and parallel combination of coaxial cables employed herein to realize the desired characteristic impedance increases the power handling capability by approximately the number of cables used. For standard coaxial cable implementation, the choice of characteristic impedances available is limited and hence, the desired characteristic impedance has to be realized using a suitable series and parallel combination of cables. Further, the fine tuning of the center frequency for the proposed

WPD and QHC is easily possible by merely trimming the cable length and it does not need elaborate fabrication process. In addition, using flexible coaxial cables it is certainly possible to achieve miniaturization in the fabricated model. Hence, novel miniaturization WPD and QHC has been designed, implemented and measured using the above approach. The measured results have been compared and found good agreement with the desired (theoretical) results as discussed in the following sections.

2. DESIGN AND DEVELOPMENT

Coaxial cables RG188 (characteristic impedance $Z_{C1} = 50\ \Omega$) and RG187 (characteristic impedance $Z_{C2} = 75\ \Omega$) with Teflon (PTFE (Polytetrafluoroethylene)) dielectric material (dielectric constant $\varepsilon_r = 2.1$) have been used in the design of WPD and QHC. The diameters of the inner conductor of RG188 and RG187 cables are 0.54 mm and 0.31 mm, respectively, with outer conductor diameter of 2 mm for both the cables.

2.1 Design of the Wilkinson Power Divider (WPD)

As shown in Fig. 1, to achieve equal power splitting (3 dB) in WPD two quarter-wavelength transmission line sections of characteristic impedance of $Z_0\sqrt{2}$ need to be used. Hence, with Z_0 is 50 Ω, the required value of the characteristic impedance ($Z_0\sqrt{2}$) is 70.71 Ω which is very near to the Z_{C2} of the available co-axial cable RG187. The layout of the proposed WPD using coaxial cables has been shown in Fig. 3, with a cable length of ($\lambda/4$) equal to 20 cm where, $\lambda = \lambda_g$ is the guide wavelength at design frequency of 260 MHz. The isolation resistor of 100 Ω is connected between the two output ports as required.

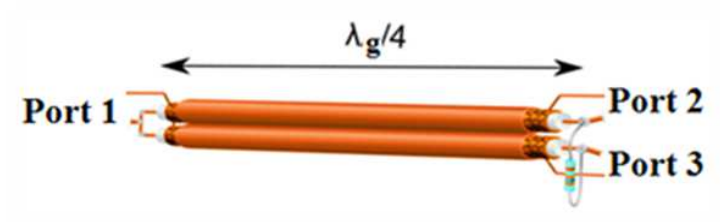

FIG. 3: Layout of proposed WPD using two coaxial cables of RG187

2.2 Design of Quadrature (90^0) Hybrid Coupler (QHC)

For equal power splitting (3 dB) in QHC two conditions should satisfy as given in (1) and (2) [2]. Hence, with Z_0 is 50 Ω, the required value of Z_{01} will be 35.35 Ω.

$$Z_{01} = \frac{Z_0}{\sqrt{2}}, \tag{1}$$

$$Z_{02} = Z_0. \tag{2}$$

In the proposed approach, the required line impedance (Z_{01}) of 35.35 Ω has been achieved by a parallel combination of two coaxial cables as done by George Badger for developing Baluns in [16]. Measurements of the characteristic impedance typically start with the input impedance of a cable section terminated in some load impedance [17]. More specifically, as depicted for a transmission line of length l, propagation constant β and characteristic impedance Z_0 is terminated in load impedance Z_L, resulting in the reflection coefficient Γ as given in (3). The largest (Z_h) and smallest (Z_l) numerical (and real) value of the input impedance Z_i respectively given by (4) and (5). The input impedance Z_i moves on a circle determined by Z_l and Z_h. Hence, the characteristic impedance Z_0 of the transmission line can be determined by (6).

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}; \tag{3}$$

$$Z_h = Z_0 \frac{1+|\Gamma|}{1-|\Gamma|}; \tag{4}$$

$$Z_l = Z_0 Z_0 \frac{1-|\Gamma|}{1+|\Gamma|}; \tag{5}$$

$$Z_0 \left(Z_h Z_l\right)^{1/2}. \tag{6}$$

By connecting two RG187 ($Z_{C2} = 75$ Ω) coaxial cables in parallel, the resultant impedance of 37.5 Ω can be achieved theoretically. It was experimentally found that due to the coupling between cables, two RG187 coaxial cables in parallel gives a characteristic impedance of 34.6 Ω when actually measured using the technique given in [17]. This slight variation in the characteristic impedance is mainly because of the change in effective dielectric constant of the resultant parallel combination of the cables. The layout of the proposed QHC using coaxial cables has been shown in Fig. 4 with Z_0 is 50 Ω. The amplitude and phase balance of the proposed QHC depends only upon the symmetry with which the cables are connected, the insertion loss improves because of the use of coaxial cables that are less lossy as compared to, say, microstrip lines [18].

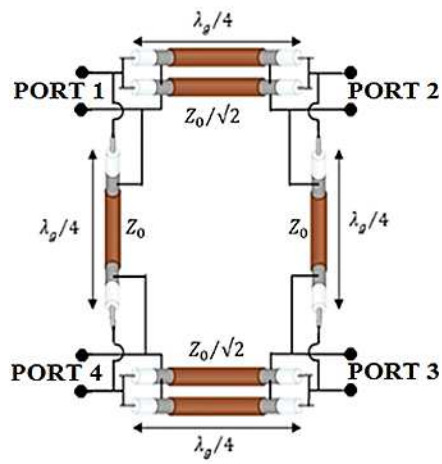

FIG. 4: Layout of proposed QHC using coaxial cables with Port 1: Input Port, Port 2: Through Port, Port 3: Coupled Port, and Port 4: Isolated Port

3. DEVICE IMPLEMENTATION

A WPD and QHC have been fabricated using readily available (50 Ω and 75 Ω) coaxial cables as discussed in earlier section and shown in Figs. 3 and 4, respectively. Input and output ports have been formed by using SMA type connectors.

3.1 An Implementation of WPD

The implementation of WPD has been carried out using coaxial cables as depicted in Fig. 5. For design frequency of 260 MHz, the required length of the each quarter-wavelength transmission line sections is 20 cm using the conventional microstrip line technique. Due to the use of flexible co-axial cables as shown in Fig. 5 it occupies the length of 9 cm only. This shows the reduction in the lengths of each of the quarter wavelength transmission line sections up to 55% at the same design frequency.

3.2 An Implementation of QHC

An implementation of QHC has been realized using coaxial cables as shown in Fig. 6. Using the conventional microstrip line implementation for design frequency of 260 MHz, the required dimension for QHC is (20 x 20) cm^2, i.e., total area of 400 cm^2. Whereas, with the help of flexible co-axial cables as shown in Fig. 6 the QHC occupies the area of (18 x 17) cm^2, i.e., 306 cm^2 only. This shows the reduction in the length and width respectively up to 10% and 15%, with overall miniaturization of 23.5% at the same design frequency.

FIG. 5: Photograph of WPD using coaxial cables

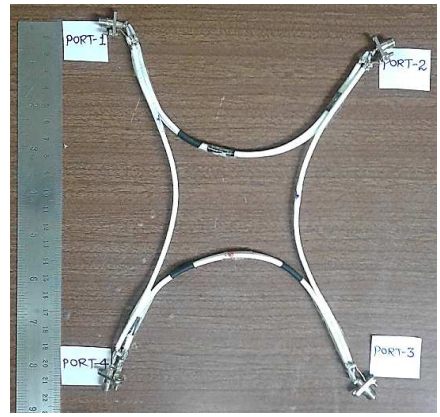

FIG. 6: Photograph of QHC using coaxial cables

4. RESULTS AND DISCUSSION

4.1 Experimental Results and Performance of WPD

Experimentally measured results of WPD are depicted in Fig. 7. The salient bandwidths of the proposed WPD have been observed. It may be seen in Fig. 7 that, the 2:1 VSWR bandwidth (BW) is from 140–327 MHz or around 71.9% and the 15 dB return loss BW is from 198–300 MHz or around 39.23%. From Fig. 7, the typical measured coupling loss at Port 3 is (S_{31}) 3.16 dB against the ideal value of 3 dB, whereas, the insertion loss (S_{21}) is 3.12 dB at Port 2, with good isolation (S_{32}) of 24 dB between the two output ports (Port 2 and Port 3). Hence, from the above details the overall well operational bandwidth (BW) of the proposed WPD is from 207 MHz to 300 MHz or fractional BW of 35.76%.

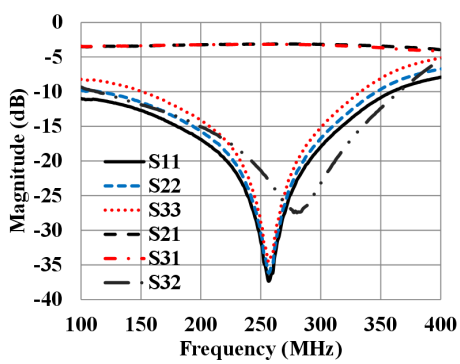

FIG. 7: Plots of Return loss at all Ports (S11, S22, S33), Insertion Loss (S21) at Port 2, Coupling (S31) at Port 3, and Isolation (S32) between Port 2 and Port 3 of WPD

4.2 Experimental Results and Performance of QHC

Measured results of the fabricated QHC are shown in Figs. 8–10. It may be seen from Fig. 8 that, the measured center frequency is 260 MHz and the 2:1 VSWR bandwidth is from 215–300 MHz or around 32.6% and the 15dB return loss bandwidth is from 235–290 MHz or around 21%. From Fig. 9, the typical measured coupling at 'Coupled Port' (Port 3) is (S_{31}) 2.91 dB against the ideal value of 3 dB, whereas, insertion loss (S_{21}) was 3.5 dB at 'Through Port' (Port 2), giving a 0.5 dB loss in the coupler. It should be remembered that this loss is despite the two cable bunch used as transmission line and includes the cable coupling losses, connector loss for input/output connections, and also losses due to limitation in the choice of characteristic impedances of standard coaxial cables.

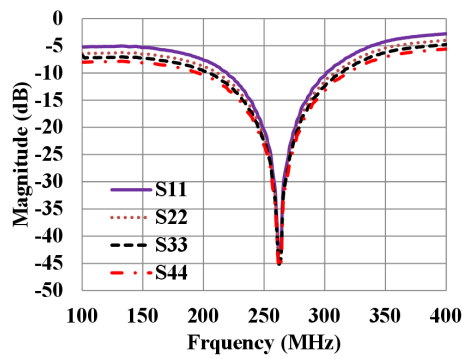

FIG. 8: Plots of Return loss at all Ports of QHC

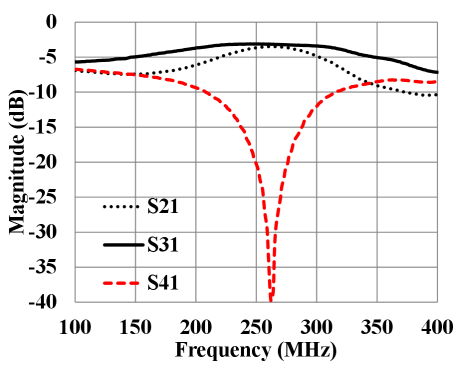

FIG. 9: Plots of insertion loss (S_{21}) at Port 2, coupling (S_{31}) at Port 3, and isolation (S_{41}) between Port 1 and Port 4 of QHC

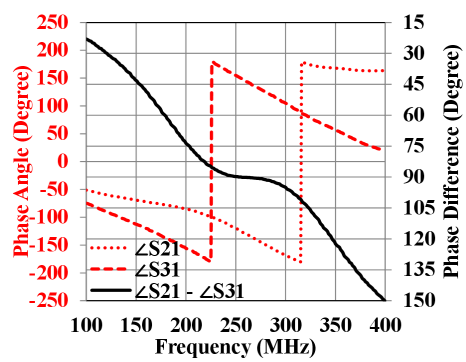

FIG. 10: Phase angle and phase difference plot

From even mode and odd mode analysis [2] of the QHC, the impedance matching at port 1 and isolation at port 4 are possible if the coupler design satisfies (7), which derives (8) for calculation of coupling factor (*C*) for the QHC. In the proposed design,

as the measured characteristic impedance (Z_{01}) for the parallel connection of two coaxial cables is 34.6 Ω using (8) the calculated coupling factor (C) is 2.8 dB which is validating the experimental value of (S_{31}) is 2.92 dB.

As seen from Fig. 9, the proposed QHC provides a high isolation (S_{41}) between the two output ports, of 39.68 dB at the center frequency of 260 MHz and better than 15 dB over the range of 238–289 MHz or 19.6%. The directivity of this QHC has been calculated by using (9) [2], and is equal to 36.7 dB. From Fig. 10, at the design frequency (260 MHz), the phase angle at port 3 is 140^0 and that at port 4 is -130.2^0, gives the phase difference between the two output ports of 89.8^0 against the theoretical value of 90^0 and shown in Fig. 10. The Fig. 10 shows the phase imbalance of $\pm 1^0$ over the range of 242–277 MHz and coupling amplitude imbalance of ± 0.2 dB over the range of 248–286 MHz. This phase imbalance and coupling amplitude imbalance have been taken into consideration as per commercial requirement of the QHC. Hence, from the foregoing discussion, it becomes apparent that the proposed QHC is well functional with respect to all the parameters over the bandwidth (BW) of 248–277 MHz or fractional BW of 11.15%.

$$\frac{Z_{02}}{Z_0} = \frac{Z_{01} / Z_0}{\left(1 - \left(Z_{01} / Z_0\right)^2\right)^{1/2}}; \tag{7}$$

$$C = 10\log\left(\frac{1}{1 - \left(Z_{01} / Z_0\right)^2}\right). \tag{8}$$

$$\text{Directivity (dB)} = \text{Isolation (dB)} - \text{Coupling (dB)}. \tag{9}$$

5. CONCLUSIONS

In this work, novel implementations of a 3 dB Wilkinson Power Divider (WPD) and Quadrature (90^0) Hybrid Coupler (QHC) have been presented using series and parallel combination of coaxial cables. This technique of combining coaxial cables is simple to realize, affords easy fine tuning of center frequency, phase trimming and is useful for designing various very high frequency (VHF) devices by suitable series / parallel combination of easily available coaxial cables. It has been demonstrated from the fabricated prototype of WPD that the reduction in the lengths of each of the two quarter-wavelength transmission line sections in terms of guide wavelength (λ_g) is up to (λ_g /8.8) cm at the design frequency (260 MHz) as compared to its conventional microstrip line design. In the case of QHC, the area of the proposed QHC is reduced up to (3.8 λ_g) cm^2 with overall size reduction of 23.5% has been achieved as compared to its conventional microstrip line design. The measured results for this presented implementation of both WPD and QHC confirm good input and output matching, low insertion loss, good isolation and coupling as desired. Such a compact WPD and QHC is useful in antenna feed networks in a high power phased array of antennas or for power combining from amplifiers, particularly at VHF applications in Radar and other RF / Wireless telecommunication systems.

ACKNOWLEDGEMENT

The authors acknowledge the support of Mr. Jagadish Prajapati and Mr. Prafull Irpache from RFMS Division, SAMEER, Mumbai during the measurements.

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