Design of a Frequency Agile Rat Race Coupler

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Abstract- **A frequency reconfigurable 180° hybrid ring having wide tunability within 1.7 GHz - 3.2 GHz range is presented. Equivalent low-pass structures of transmission lines are used for original circuit modification and capacitors are replaced by varactor diodes for continuous tuning purpose. The proposed circuit can provide equal power division with 0°, 180°phase difference at different operating frequencies by simultaneously tuning six varactors. The circuit is designed on low cost FR-4 substrate and has also compact dimension (0.17λ×0.27λ×0.127λ) at 2.5 GHz, 50% less than conventional configuration.**

I. INTRODUCTION

In recent years mainstream of all communication systems are oriented towards development of multifunctional devices covering diverse frequencies of operation. Concurrently the physical dimensions of the devices are moving towards miniaturization, which is adding more design complexity to the architecture of front end radio terminals. In this scenario development of different types of frequency agile microwave passive devices having reduced dimension for RF-transceiver systems has become a hotspot for all researchers.

Basically tunability in microwave circuits is achieved by using different types of active devices like semiconductor diodes (p-i-n, varactors), ferroelectric varactors and microelectromechanical systems (MEMS) etc. [1]. Successful implementation of different types of frequency agile devices using active components are done in several communications [2-4]. In this article design of a frequency reconfigurable 180° hybrid ring within 1.7 GHz-3.2 GHz range is presented.

II. DESIGN METHODOLOGY OF RECONFIGURABLE RAT-RACE

The 180° hybrids have ability of power summation and equal power division with 0° and 180° phase difference similar to magic tees. These couplers are very much popular in design of balanced mixers, balanced amplifiers and image-rejection couplers used in MMICs. Conventional rat-race coupler (180° hybrid ring) comprises of one $3\lambda_g/4$ and three $\lambda_g/4$ transmission lines in which quarter wave transmission line act as main building block.

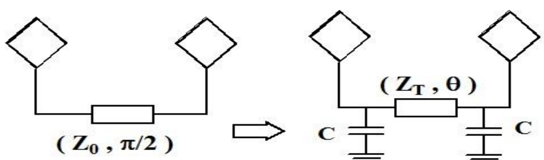

Fig. 1. Quarter wave transmission line and its low pass equivalent

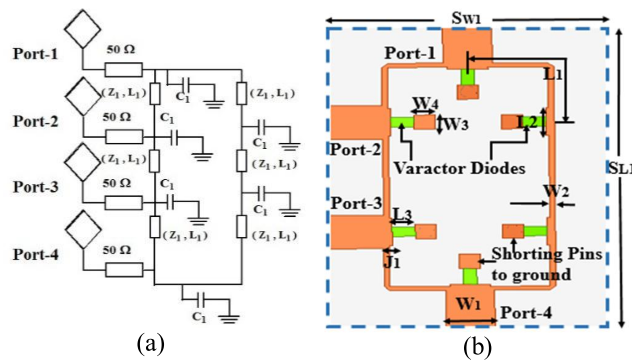

Fig. 2. Reconfigurable rat-race coupler (a) Circuit equivalent (b) Layout

Therefore the basic design methodology of the frequency reconfigurable rat-race coupler is to replace the quarter wave length transmission lines with their equivalent low pass structures [5]. The objective of this type of transformation is to achieve a transmission line having shorter length than $\lambda_g/4$, higher impedance value to offset the inductance and using lumped capacitance to compensate capacitance loss. A quarter wave length transmission line and its corresponding low pass equivalent using two capacitors across a high impedance shorter line is shown in Fig. 1. Equations (1) and (2) illustrate the admittance matrix of the two circuits where Z_0, Z_T, θ, ω are the characteristic impedance of the quarter wave-length line, the characteristic impedance of the modified line, electrical length of the shortened line, and the angular frequency respectively.

$$[Y_1] = \frac{1}{jZ_0}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{1}$$

$$[Y_T] = \begin{bmatrix} \frac{\cos\theta}{jZ_T \sin\theta} + j\omega C & \frac{1}{jZ_T \sin\theta} \\ \frac{1}{jZ_T \sin\theta} & \frac{\cos\theta}{jZ_T \sin\theta} + j\omega C \end{bmatrix} \tag{2}$$

Equating the two equations, some empirical relations can be derived as follows

$$Z_T = Z_0/\sin\theta \tag{3}$$

$$\omega C = (1/Z_0)\cos\theta \tag{4}$$

For present case characteristic impedance of the $\lambda_g/4$ section is taken as 70.71 Ω and the impedance of the modified line is chosen as $Z_1=Z_T=100\ \Omega$. The calculated length of the modified transmission line is $\theta = L_1 = \lambda_g/8$ (45°) and the capacitance value of $(C_1/2) = 0.63$pF for an operating frequency of 2.5 GHz. The rat race coupler is initially designed on a 60 mil thick FR-4 at a center frequency of 2.5 GHz. The six quarter wavelength lines, connected end to end are replaced by six $\lambda_g/8$ high impedance lines with a pair of parallel capacitances connected to ground at each end (later replaced by equivalent capacitances). From (4) it is important to observe that the use of lumped capacitance provide a degree of freedom to control the operational frequency of the device within a wide range.

III. Simulation And Result Analysis

The circuit equivalent of the modified rat-race coupler is designed and simulated using ANSYS DESIGNER-15 shown in Fig.2 (a). To achieve frequency reconfigurability using continuous tuning method, appropriate varactor diode models (SMV2019, Skyworks Solutions Inc.) are employed in place of capacitors. The values of six capacitance are altered simultaneously following the datasheet of the varactor diode for different reverse bias voltages. Simulation results of the circuit for different capacitance values of 0.4pF (8V), 1.2pF (2V) and 1.33pF (1.5V) are presented in Fig. 3, which shows that the coupler can be operated at different frequencies between 2.0 GHz to 4.0 GHz. Full wave analysis of the circuit using ANSYS HFSS 15.0 shows some amount of impedance mismatch between the ports due to use of extra stubs for insertion of physical varactors. To mitigate this mismatch loss, the circuit is optimized using HFSS and some change in impedance values along with shifting of operating frequency are noticed.

TABLE I

Design Parameters And Their Optimized Values

Parameters	Values (mm)	Parameters	Values (mm)
$SW_1 \times SL_1$	20.6× 32.4	L_1	5.9
W_1	3.6	L_2	2.98
W_2	0.44	L_3	1.7
W_3, W_4	0.76	J_1	0.2

The final dimensions of the circuit are provided in Table I. Scattering parameters and phase difference between different ports for different capacitance values achieved by reverse voltage variation of the varactor diode are presented in Fig.4. From the figure, it is clear that by increasing the capacitance values of the varactors from 0.3 pF to 1.33 pF the operating frequency of the device decreases from 3.2 GHz to 1.7 GHz.

IV. Conclusion

The proposed frequency agile rat-race coupler operates at different frequencies of 3.0 GHz, 2.4 GHz, 1.9 GHz depending upon variable reverse bias voltage of 19V(0.3pF), 5V(0.66pF) 1.5V(1.33pF) applied to the six varactor diodes. Very less amplitude and phase imbalance (±0.1 dB, ±2˚), reflection co-efficient less than -10dB along with isolation less than -25dB are observed between the output ports at all achieved frequencies within the intended range. Suitable space filling methods may be used to reduce the size to make the circuit useful for MMICs.

References

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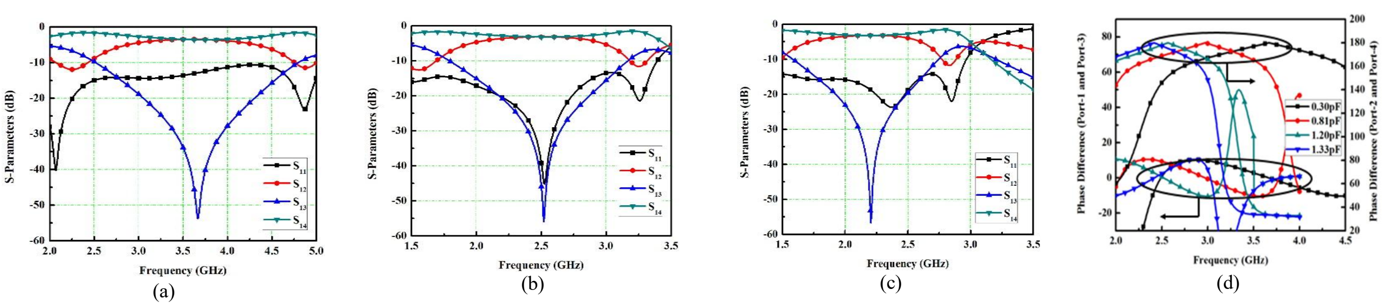

Fig. 3. S-parameters of the circuit using ANSYS Designer for different capacitance values (a) 0.4pF (b) 1.2pF (c) 1.33pF (d) Phase difference between outputs

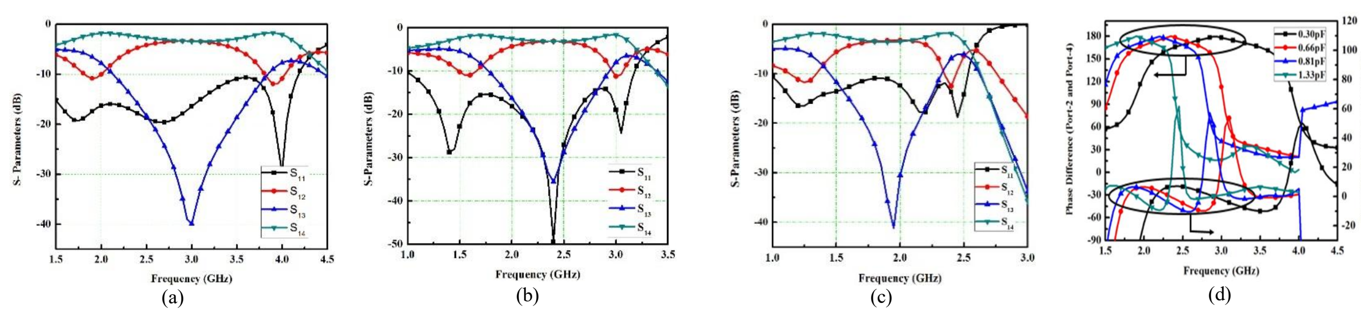

Fig. 4. S-parameters of the circuit using ANSYS HFSS for different capacitance values (a) 0.3 pF (b) 0.66 pF (c) 1.33 pF (d) Phase difference between outputs