Directional Coupler with High Isolation Bandwidth using Electrical Balance

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***Abstract*—A directional coupler using edge coupled lines is designed and fabricated on a two-layer PCB with isolation being achieved through electrical balance. Measured results show 4dB coupling and 34dB isolation at a frequency of 2.5GHz with 16% matching bandwidth (-10dB). Isolation varies between 31dB to 36dB in the 2.3GHz to 3GHz frequency range.**

***Index Terms*—Directional coupler, isolation, electrical balance**

I. INTRODUCTION

Directional coupler is an important building block in microwave circuits. Traditional directional couplers are made using quarter-wave transmission lines where isolation is achieved by splitting the signal into two parts which travel different path lengths to become out of phase. The signals from the two paths are then added together at the isolated port [1]. Use of coplanar waveguides in place of microstrip transmission lines (TL) improves directivity and bandwidth but provides low coupling [2]. Edge-coupled lines with controlled even and odd mode impedance can realize a coupler with high coupling coefficient [3]. In all these couplers, complete isolation happens only at one frequency and the isolation bandwidth is close to the matching bandwidth.

In this work, edge-coupled line based directional couplers are proposed, where electrical balance is used to achieve isolation. Electrical balance exploits symmetry of the network and is therefore independent of frequency, resulting in high isolation bandwidth. A hybrid transformer [4] also uses electrical balance to isolate ports but the frequency of operation is limited by parasitic capacitances. Moreover, there is high common-mode leakage to the isolated port [5].

In section II, the operation of the proposed directional coupler is discussed. The detailed design of the coupler on a double-layer PCB is covered in section III. Measured results are compared with simulation results in section IV, followed by conclusions.

II. DIRECTIONAL COUPLER WITH ELECTRICAL BALANCE

The proposed directional coupler is shown in Fig. 1 along with a valid set of port and TL impedances. Port 4 is a balanced port. T1 and T2 are quarter-wave edge coupled lines with very high even mode impedance. The operation of the circuit for excitation at different ports is explained below:

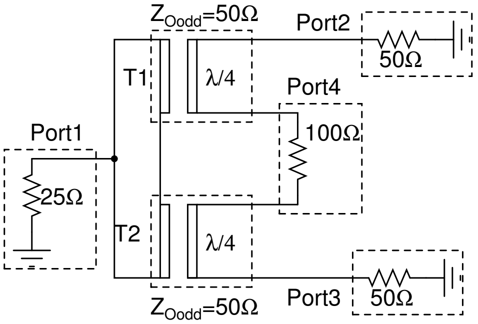

Fig. 1. Schematic of proposed directional coupler

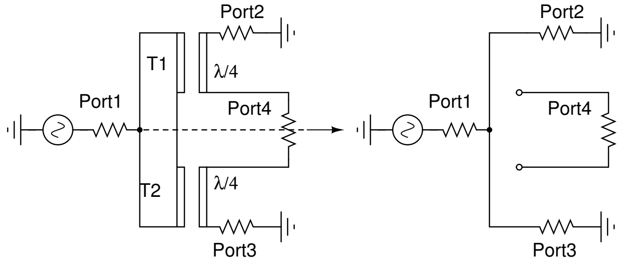

Fig. 2. Equivalent circuit for signal at port 1

1) *Signal applied at port 1*: For port 1 excitation, the network is symmetric about the line passing through port 1 and middle of port 4 (Fig. 2). Therefore, port 4 is open circuited and T1 and T2 can be treated as open circuited quarter-wave lines, providing a short-circuit at their other ends. The circuit now reduces to port 1 feeding a parallel combination of port 2 and port 3. For matching at port 1, $R_1 = R_2||R_3$, where R_i denotes port i impedance.
2) *Signal applied at port 2*: Even and odd mode analysis can be utilized to understand this case. Even mode equivalent circuit is similar to Fig. 2, with equal signals being applied at ports 2 and 3 instead of port 1. In odd mode, signals applied at ports 2 and 3 are out of phase. Hence the nodes through which the line of symmetry passes become virtual ground (Fig. 3). High even mode impedance makes sure that only odd mode current flows in T1 and T2. There is no reflection at ports 2 and 3 when

$$R_2 = R_3 = \frac{Z_{Oodd}^2}{R_4/2} \tag{1}$$

In this mode, all of the applied power appears at port 4 with a phase delay of 90^0. Superposition of the two modes give zero signal at port 3 while power entering

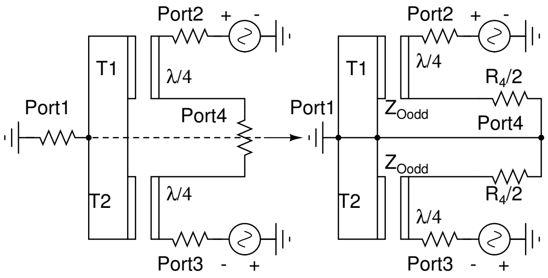

Fig. 3. Equivalent circuit for odd mode signals at ports 2 and 3

in port 2 is divided equally between ports 1 and 4.

The above analysis shows that port pairs 1-4 and 2-3 are isolated with respect to each other. Moreover, power entering at any port divides equally between coupled ports. Thus, the scattering matrix (S) will have the form:

$$[S] = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -j \\ 1 & 0 & 0 & j \\ 0 & -j & j & 0 \end{bmatrix} \tag{2}$$

Although signal can be applied to any port, isolation behaviour when input is applied at port 1 is discussed below.

A. Effect of mismatch

Isolation depends on electrical balance present in the network. Any kind of mismatch can destroy symmetry and reduce isolation. Mismatches from several sources are possible in practical design:

1) *Length mismatch of TL*: Length mismatch between T1 and T2 causes a net voltage to appear across port 4 resulting in reduced isolation. It can be shown that isolation is inversely proportional to $\frac{\delta L}{\lambda}$, where δL is the length mismatch between T1 and T2.
2) *Mismatch between ports 2 and 3*: Difference in impedances of ports 2 and 3 causes different currents in the ports. This asymmetry is enough to cause imbalance at port 4 and reduce isolation.

B. Common mode coupling between port 1 and port 4

When input is applied at port 1, ends of T1 and T2 close to port 4 see maximum voltage swing because differential current is forced to zero at those ends (Fig. 2). If port 4 has finite common mode impedance then port 4 nodes will be maintained at ground while the other floating ends of T1 and T2 will see the common mode swing. Ports with pseudo-differential stage or centre-tapped balun as front-end have very low common mode impedance and can reduce common mode coupling.

C. Out of band rejection in full duplex front-end

Full duplex communication can be achieved if transmitter is connected to port 1, antenna is connected to port 2 and receiver is connected to port 4. High isolation bandwidth will protect receiver from out of band noise and interference of transmitter.

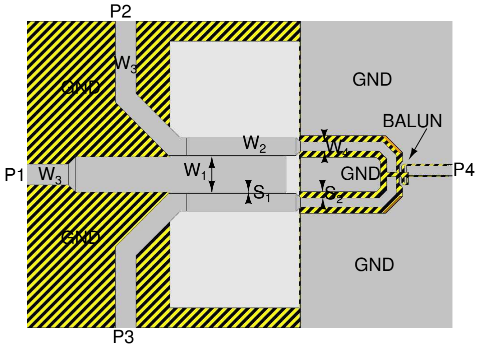

Fig. 4. Layout of final design. Grey region denotes top conductor, hatched region denotes bottom conductor and rectangular white patch shows etched region in bottom plane.

TABLE 1

Geometry Dimensions

Dimension	Value (in mils)
W_1	225
W_2	112.5
S_1	10
W_3	132
W_4	60
S_2	40

III. DESIGN OF COUPLER

The coupler is to be used for transmitter and receiver isolation in a full duplex transceiver. To get equal loss in both transmit path and receive path, 3dB coupling is kept. It is designed on a 60mils RO4003C ($\epsilon_r = 3.38$) double layer PCB. Fig. 4 shows the layout of the final design with indicated dimensions given in Table 1. First step involves design of the coupled lines T1 and T2. The spacing between the lines is kept to be equal to the minimum allowed by the fabrication facility (10mils). This gives maximum odd mode capacitance, resulting in thinner lines for the same impedance. The ground plane below the lines is removed to increase even mode impedance. From the circuit figure (Fig. 1) we can see that one line each from T1 and T2 are connected to same nodes. Therefore, the two lines can be merged together as in Fig. 5. The length of the merged line is designed to be slightly

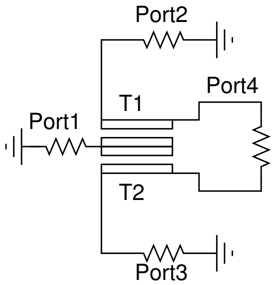

Fig. 5. T1 and T2 merged together to have a common return path

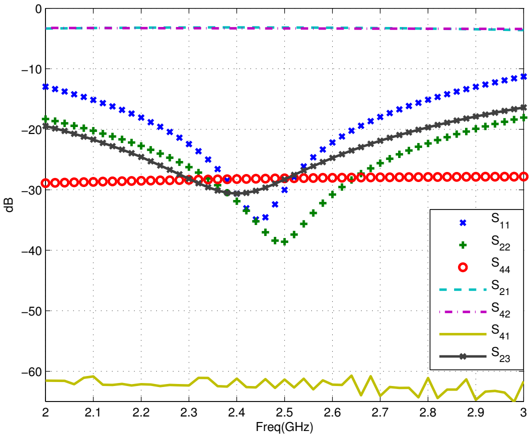

Fig. 6. Simulation result of coupler without impedance transformer and balun

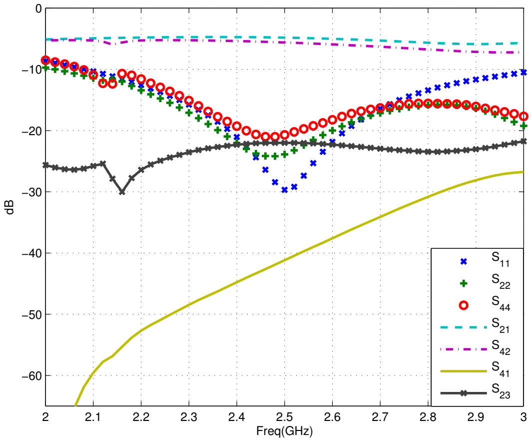

Fig. 7. Simulation result of final design

less than $\lambda/4$ to compensate for the extra capacitance added by the open circuit.

For measurement purposes, all ports are designed for 50Ω impedances. A quarter wave TL is used to transform 25Ω to 50Ω at port 1. The width of the merged line of T1 and T2 is matched to the quarter wave TL at port 1. Port 4 is connected to T1 and T2 by quarter wave CPW lines which make the looking-in impedance at port 4 equal to 100Ω. Finally, a 100:50 balun (Minicircuits NCS2-33) converts port 4 into a 50Ω unbalanced port.

IV. SIMULATION AND MEASURED RESULTS

All simulations are done using Sonnet v13. Considering the port definitions of Fig. 1, the results of a simulation without impedance transformation at port 1 and 4 is shown in Fig. 6. Finite isolation (S_{41}) is due to asymmetry caused by meshing algorithm of the software. The simulation results on the final design (Fig. 4) is shown in Fig. 7. In this case, the isolation shows strong frequency dependence due to imbalance in the balun. The fabricated board (Fig. 8) is characterized using an Agilent 5071C ENA network analyzer. The important scattering parameters from the measured results are plotted in Fig. 9. S_{21} is -4dB, S_{42} is -3.6dB and isolation $(1/S_{41})$ is 34dB at the centre frequency of 2.5GHz. Input matching is better than 10dB in 2.3GHz to 2.7GHz frequency range at all the ports. Isolation varies between 31dB to 36dB in 2.3GHz to 3GHz range.

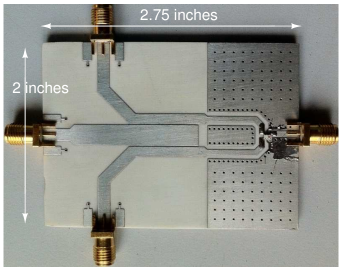

Fig. 8. Image of fabricated board

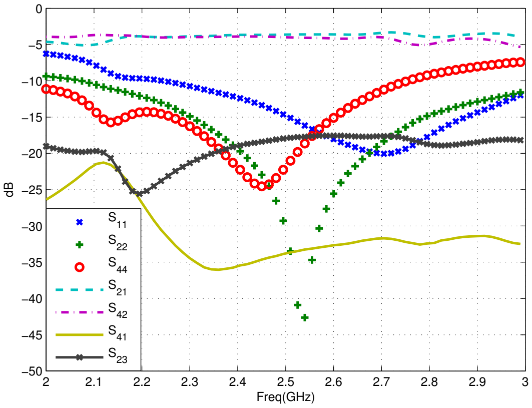

Fig. 9. Measured result of designed board

V. CONCLUSION

A new directional coupler using electrical balance for isolation is presented. High isolation achieved in this design is theoretically frequency independent but asymmetry in practical design causes frequency dependence. In duplexer applications, it can reject in-band as well as out-of-band interference and noise from the transmitter.

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