TU2E-5

Analysis and Design of a High-Performance Planar Marchand Balun

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Abstract — **This paper presents an enhanced Marchand balun that offers excellent amplitude and phase balance performance. The enhanced Marchand balun is designed using compensated coupled lines. It employs capacitive compensation, a renowned technique for compensating the unequal even- and odd-mode phase velocities encountered in parallel-coupled microstrip. Analysis carried out in this study has proven that the finite directivity of coupled lines significantly affects the balun performance. The proposed capacitively-compensated Marchand balun is demonstrated at 2.1GHz and has offered excellent results.**

I. INTRODUCTION

Baluns, capable of transforming a signal between balanced and unbalanced modes, are used in the design of circuits in balanced or push-pull configuration. In particular, the Marchand balun has been extensively employed in balanced mixers and push-pull amplifiers that are required in the design of demanding wireless systems [1]. The planar Marchand balun consists of two coupled sections, which may be realised using microstrip coupled lines, Lange couplers, multi-layer coupled structures or spiral transformers. Of these the coupled line types are the simplest form.

Coupled lines are useful and widely applied structures that provide the basis for many types of components, including directional couplers, power splitters and combiners, duplexers, filters, phase shifters, transformers and the aforementioned baluns. In this study, the planar Marchand balun has been analysed as a combination of two identical coupled sections. This can simplify the balun design to designing couplers with the appropriate coupling factor [2]. In an inhomogenuous medium, such as in the case of microstrip where there is partly air and partly dielectric, the odd- and even-mode phase velocities are unequal [3]. The even-mode has less-fringing field in the air region than the odd-mode. Thus, its effective dielectric constant should be higher, indicating a smaller phase velocity for the even-mode. In the case of a directional coupler, this inequality will manifest itself in the coupler's poor directivity [4]. This is a measure of the coupler's ability to isolate forward and backward waves. The directivity performance becomes worse as the coupling is decreased or as the dielectric permittivity is increased.

II. CAPACITIVE-COMPENSATED BALUN

Several techniques are available to equalize or compensate the phase velocity inequality in microstrip couplers. These are the "wiggly lines", dielectric overlays and capacitive compensation methods [5-6]. Among them, the capacitive compensation technique has been widely adopted and analysed by various researchers to achieve high performance directional couplers [7-8]. Compensation can be implemented by employing capacitors at each end of the coupled lines. The capacitor will not affect the even-mode but effectively increases odd-mode phase length. This will increase the directivity and thus provide broadband characteristics with good isolation. With these velocity compensated coupled lines, a high performance coupled bandpass filter has been demonstrated [9]. In this study, the capacitive compensation technique is further exploited and extended to the design of a high performance Marchand balun. The proposed enhanced Marchand balun, as shown in Fig. 1, comprises of two of these capacitively-compensated coupled line sections in cascade.

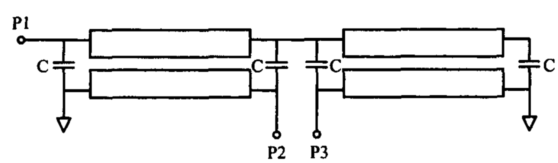

Fig. 1. The schematic of the proposed capacitive-compensated Marchand balun.

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III. ANALYSIS

When analysing the Marchand balun as two coupled line sections connected in cascade, the isolated ports of the couplers will actually be the two unbalanced ports of the balun. Therefore, any of the undesired effects due to even- and odd-mode phase velocity inequalities would inevitably contribute to the balun's amplitude and phase performance. Using microwave network theory detailed in the literature [10], the two coupled-line sections, each represented by a 4-port network, can be reduced and interconnected to give the overall S-matrix of the balun. This assumes that all the network ports are terminated in matched loads. For a non-ideal balun, its S-parameters are derived as in equation (1) and (2), assuming perfect matching in the couplers. In this case, the transmission coefficient, T, is defined as the power directed to the output after coupling and power loss to isolated port, $P_{c,41}$, and is given by (3).

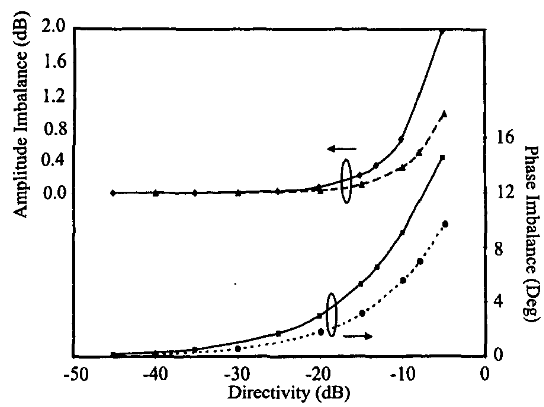

Fig. 2. A graph of coupler's directivity to Balun performances – 50-50 Ω Balun (———) and 50-230 Ω Balun (- - - -).

$$S_{b,21} = P_{c,41} + jk\sqrt{T} - \frac{(-j\sqrt{T}-kP_{c,41})(j\sqrt{T}P_{c,41}+k)(1+k^2)\left[-P_{c,41}^2+\frac{(-j\sqrt{T}-kP_{c,41})^2}{1+k^2}\right]}{P_{c,41}^4+k^2P_{c,41}^4-P_{c,41}^2(-j\sqrt{T}-kP_{c,41}^2)^2-1-k^2} \quad (1)$$

$$S_{b,31} = -\frac{(-j\sqrt{T}-kP_{c,41})(1+k^2)\left[k+j\sqrt{T}P_{c,41}+\frac{(jk\sqrt{T}+P_{c,41})(-j\sqrt{T}-kP_{c,41})}{1+k^2}\right]}{P_{c,41}^4+k^2P_{c,41}^4-P_{c,41}^2(-j\sqrt{T}-kP_{c,41}^2)^2-1-k^2} \quad (2)$$

$$T = 1 - k^2 - P_{c,41}^2 \quad (3)$$

Based on this analysis, the amplitude and phase imbalance of a 3dB balun with 50-50 Ω and 50-230 Ω transformation are plotted in correspondence to the couplers' directivity. This is shown in Fig. 2. The performances of the impedance transforming balun are obtained through de-embedding using HPADS™.

IV. BALUN DESIGN

To validate the analytical results and demonstrate the design approach, two baluns are designed, the conventional balun and the enhanced balun for comparison. The baluns are designed for impedance transformation of 50 Ω to 230 Ω using FR4 (ε_r=4.55) as dielectric with height of 1.6mm. This will need only a loose coupling factor which is achievable with the available FR4 process. The required coupling factor, k, for optimum balun performance can be found by using [2];

$$k = \frac{1}{\sqrt{\frac{2Z_L}{Z_o}+1}} \quad (4)$$

where Z_L = load impedance and Z_o = system impedance (usually 50 Ω). The compensation capacitor is given by [3];

$$C = \frac{1}{4\Pi f_o Z_{oo} \tan\vartheta_0} \quad (5)$$

where,

$$\vartheta_0 = \frac{\Pi}{2}\sqrt{\frac{\varepsilon_{effo}}{\varepsilon_{effe}}} \quad (6)$$

and f_o = frequency of operation, Z_{oo} = odd-mode characteristic impedance, ϑ_o = odd-mode electrical length of the coupled section.

With $Z_L = 230\ \Omega$ and $Z_o = 50\ \Omega$, a coupling factor of 10dB is required. This gives the coupler's width of 2.0mm and a spacing of 0.1mm. In addition, with f_o = 2.1GHz, $Z_{oo} = 36\ \Omega$ and ϑ_o= 1.38 radians, the required capacitor is then calculated as 0.2pF. The length of the couplers employed in the conventional Marchand balun is 23mm each, whereas the capacitive-compensated one is 19mm each. This is a reduction of about 18%, and results from the inclusion of the compensation capacitors. All the dimensions are initially calculated using *LINECALC*™ (by Libra), and thereafter optimized using the electromagnetic simulator, *em*™ (by Sonnet). The capacitors are designed using the interdigital types and determined using *em*™.

V. EXPERIMENTAL RESULTS

The fabricated Marchand baluns were measured using an HP8510 vector network analyzer with an SOLT calibration. The measured results of the impedance transforming balun were then de-embedded on HPADS™ to achieve the required Z_L of 230 Ω.

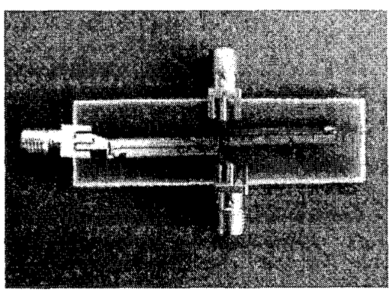

Fig. 3. The fabricated enhanced Marchand balun.

The fabricated capacitive-compensated Marchand balun, shown in Fig. 3, exhibits a coupling loss of 3.8dB and a return loss better than -30dB at 2.1GHz. Whereas, coupling loss of 4.2±0.4dB and return loss better than –10dB were achieved between 2 - 2.25GHz, a 250MHz operational bandwidth. The impedance transforming features does reduce the bandwidth of operation. In general, the larger the transformation ratio, the smaller the achievable bandwidth. In comparison with the conventional balun, the operational bandwidth attained by the enhanced balun has however increased by about 65%. The capacitive compensation has also improved the amplitude and phase imbalance performance of the conventional balun, as shown in Fig. 4.

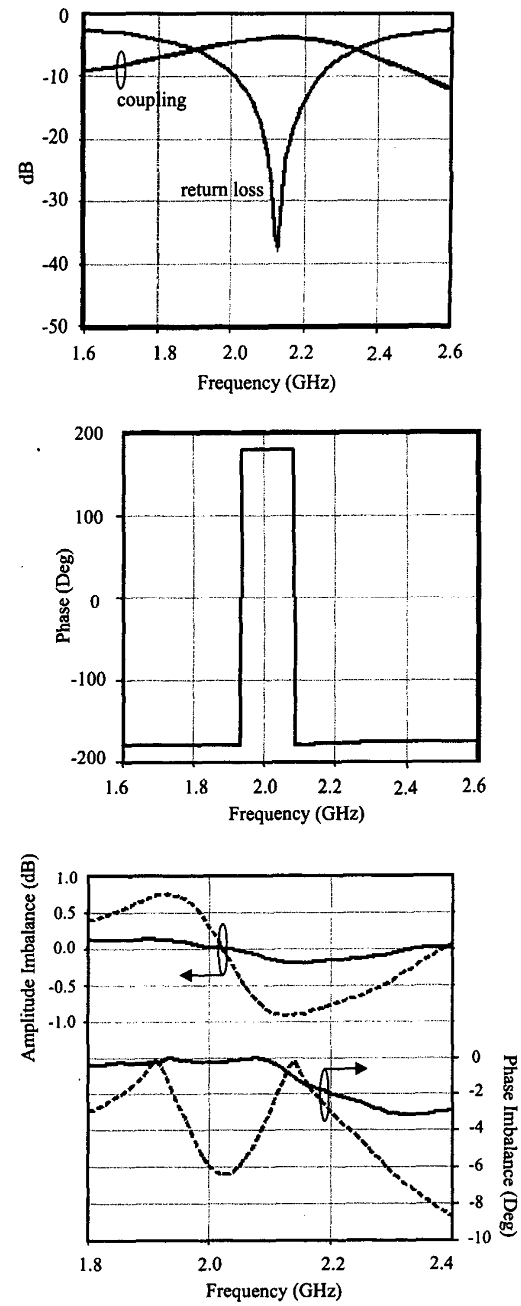

Fig. 4. Measured performances of the capacitive-compensated (———) and conventional (- - - -) Marchand balun.

Port 2 and port 3 have, across the operational bandwidth, worst cases amplitude imbalance of 0.2dB and phase imbalance of 2°. Whereas, the conventional Marchand balun performance as shown with dotted lines, shows worst case amplitude imbalance of 0.9dB and phase imbalance of 6°.

To illustrate the improvements analytically, the directivity of the normal and the compensated coupler at the operating frequency was determined in this experiment, they are –8dB and –20dB, respectively. Referring to Fig. 2, an improvement of 0.7dB amplitude balance and 4° phase balance can be obtained when the Marchand balun is compensated for phase velocity inequalities. These improvements assume that the balun port 2 and port 3 balance performances are due primarily to the directivity of the coupler as near perfect matching is achieved in these couplers. The measured performances are hence in very good correspondence with the analytical results.

VI. CONCLUSION

A planar Marchand balun can be analyzed in terms of two cascaded coupled lines, and in an inhomogenuous medium, such as microstrip, the coupled lines have unequal even- and odd-mode phase velocities, thus, leading to poor directivity. We have shown that this poor directivity would in turn cause poor amplitude and phase balance performances of port 2 and port 3 of the Marchand balun. This study has presented the analytical results and demonstrated the design approach by using a capacitively-compensated impedance transforming Marchand balun. With this, the proposed Marchand balun is capable of providing nearly ideal performances, and together with the feature of size reduction, it would be beneficial to the many demanding systems needed in microwave applications.

ACKNOWLEDGEMENT

The authors wish to acknowledge EPSRC (UK) and Mahanakorn University of Technology for their financial support and Mr. D.I. Dryden from the Electronic Workshop for providing the fabrication expertise.

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