DESIGN OF PLANAR, SINGLE-LAYER MICROWAVE BALUNS

Dan Raicu
California Eastern Laboratories
4590 Patrick Henry Drive
Santa Clara, California 95054

ABSTRACT

This paper describes a microstrip balun as an elementary odd-mode launcher, cascaded with a transversely symmetric network acting as an even-mode stopband filter and an odd-mode impedance transformer. The proposed methodology is illustrated by the design of a rigorously two-dimensional balun with high performance in the range 2.1-3.6 GHz. Such a structure is easy to integrate in microstrip circuits, low cost and free of the parasytics affecting the high frequency operation of other baluns.

INTRODUCTION

Applications like push-pull amplifiers or mixers require at input and produce at output signals of equal magnitude and opposite phase. By a questionable extension of the conventional RF concepts, hybrid microwave circuits used to obtain such signals are often called baluns although their output is not a balanced line but rather a pair of unbalanced (usually microstrip) lines carrying an odd-mode signal. There is a clear distinction between these cases. While in the balanced line the propagating wave is supported by the two identical conductors (as evidenced by the origin and end of the electric field lines), in the odd-mode pair the power is carried almost exclusively between each conductor and the ground, with only a small fraction of electric field lines extending between the two live conductors. Beyond the terminology issue, this stretching of the RF concepts translated into efforts aimed towards an adaptation of classical balun configurations to microstrip implementation, for which they may not be well suited (examples can be found in textbooks such as [1] or [2]). Such microstrip baluns depart from the true planar microstrip configurations by requiring multiple layers, cavities in the ground, via holes, bondwires etc. The present work presents the design and performance of a true-microstrip balun, as well as general indications regarding the synthesis of such structures.

Consider a microstrip three-port (in which, for discussion purposes, we will identify one input and two outputs). Unless it happens to be an equal-amplitude in-phase power divider, any such three-port will typically split an incoming signal into two unequal, out-of-phase emerging signals. We can regard them as the superposition of an even-mode and an odd-mode pair of signals. The basic idea is to follow this three-port by a network that will suppress the even-mode, and meanwhile enhance the odd-mode by compensating the reflections that affect its magnitude.

This is best accomplished by a four-port network with transverse symmetry. Such a circuit can be analyzed separately for the odd-mode and the even-mode, by bisecting it along the symmetry axis with a magnetic, respectively electric wall, and considering for each mode just one of the two identical halves. We want the even-mode equivalent to represent a stop-band filter in the specified frequency range, preventing the even-mode component existent at its input to reach the output. The odd-mode equivalent however is required not merely to allow unimpeded propagation of the respective signal, but also to cause the cancellation of the overall reflections at the input of the preceding three-port, in other words to act as a matching impedance transformer.

It makes sense not to start from any arbitrary three-port, but rather to select one that, to begin with, emphasizes at the output the odd-mode versus the even-mode. We will call such a three-port an elementary odd-mode launcher. It can be as simple as a symmetric T-junction with output arms differing in length by $\lambda/2$. Such a launcher can work accurately at a single frequency. At a different frequency the phase difference at the output shifts from 180^o and the magnitudes are not maintained equal either, unless the arms happen to be matched. As a result, the launcher output will include besides the odd-mode component an undesirable even-mode component.

ANALYSIS

Consider the general three-port from Fig. 1a. At its input port, 1, and its two output ports, 2 and 3, the incident waves are denoted $a_{i,}$ and the emergent waves, b_i. Their complex magnitudes are linearly related, by the scattering coefficients S_{ij}. Insofar as $b_2 \neq b_3$, we can regard them as the combination of an even-mode pair of signals of magnitude b_{ev} and an odd-mode pair of signals of magnitude b_{odd}.

$$b_2 = \frac{\sqrt{2}}{2}\left(b_{ev} + b_{od}\right) \qquad (1a)$$

$$b_3 = \frac{\sqrt{2}}{2}\left(b_{ev} - b_{od}\right) \qquad (1b)$$

in which we defined

$$b_{ev} = \frac{\sqrt{2}}{2}\left(b_2 + b_3\right) \qquad (2a)$$

$$b_{od} = \frac{\sqrt{2}}{2}\left(b_2 - b_3\right) \qquad (2b)$$

and, since port 1 is the input, we can add the identity

$$b_{in} = b_1 \qquad (2c)$$

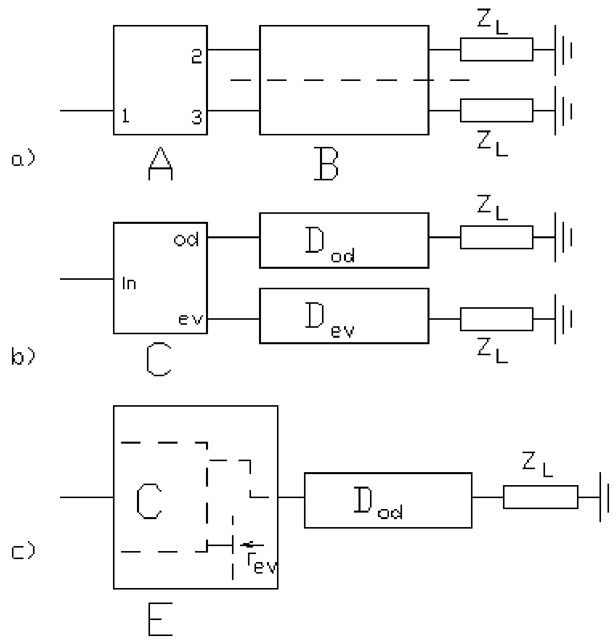

Fig.1: a) Schematic of the balun b) Odd-mode and even-mode equivalent c) Odd-mode equivalent when even-mode is suppressed ($\Gamma_{ev} = \exp j\varphi$)

Equations of a similar form relate the incident waves at the three ports, a_1, a_2 and a_3 to similarly defined a_{ev}, a_{od} and a_{in}. It is now easy to calculate a modified scattering matrix relating the newly defined components of the column matrices b and a. Indeed, we find that:

$$\begin{Vmatrix} b_{in} \\ b_{ev} \\ b_{od} \end{Vmatrix} = \begin{Vmatrix} \sigma_{ii} & \sigma_{ie} & \sigma_{io} \\ \sigma_{ei} & \sigma_{ee} & \sigma_{eo} \\ \sigma_{oi} & \sigma_{oe} & \sigma_{oo} \end{Vmatrix} \bullet \begin{Vmatrix} a_{in} \\ a_{ev} \\ a_{od} \end{Vmatrix} \qquad (3)$$

in which

$$\left.\begin{aligned} \sigma_{ii} &= S_{11} \\ \sigma_{ee} &= \tfrac{1}{2}(S_{22} + S_{33}) + S_{32} \\ \sigma_{oo} &= \tfrac{1}{2}(S_{22} + S_{33}) - S_{32} \\ \sigma_{io} = \sigma_{oi} &= \tfrac{\sqrt{2}}{2}(S_{12} - S_{13}) \\ \sigma_{ie} = \sigma_{ei} &= \tfrac{\sqrt{2}}{2}(S_{12} + S_{13}) \\ \sigma_{eo} = \sigma_{oe} &= \tfrac{1}{2}(S_{22} - S_{33}) \end{aligned}\right\} \qquad (4)$$

In this way we replace the circuit from Fig. 1a by its equivalent from Fig. 1b. The three-port A is replaced by a "virtual" three-port C, where the two output ports are no longer distinct in location, but rather represent the odd mode and the even-mode. Correspondingly, C is cascaded with two different uncoupled two-ports, D_{od} and D_{ev}, equivalents to the symmetric network B for these two modes.

In order to obtain a pure odd-mode in the load, the two-port D_{ev} needs to be a perfect band-stop filter, therefore to present at its input a reflection coefficient equal in magnitude to 1, in other words

$$\Gamma_{ev} = e^{j\varphi} \qquad (5)$$

in which φ is a function of frequency. With this observation, we arrive at the circuit from Fig. 1c, where the three-port C reactively terminated at its even port becomes a lossless two-port E, with a new scattering matrix σ' that can be easily recalculated, cascaded with the two-port D_{od} from Fig. 1b. By well-known procedures we can now calculate the reflection coefficient Γ_{od} (itself a function of frequency) that is required at the input of D_{od} in order to have an impedance match at the input of the two-port E. Designing the balun means eventually to synthesize a symmetric network B (Fig. 1a) characterized at its input side by the reflection coefficients Γ_{ev} and Γ_{od} for the even- and odd-mode respectively.

Practically, this synthesis is a very complex task. An alternative could be to design the symmetric network just for the requirement of even-mode filtering, to determine its reflection coefficients for the two eigen-modes and then design the input three-port as a matching circuit.

Any design however would require anyway the use of computer optimization. It is more convenient therefore to regard the above analysis just as a guideline for establishing a starting network topology, with a simple odd-mode launcher followed by a symmetric network showing stop-band filter properties when bisected by an electric wall, including a sufficient number of variables and optimizing them simultaneously for a specified even/odd-mode ratio and a specified input return loss in the required frequency range.

PRACTICAL REALIZATION

Fig. 2 illustrates the concept described above by a balun that was designed and tested for the frequency range 2.1 - 3.6 GHz.

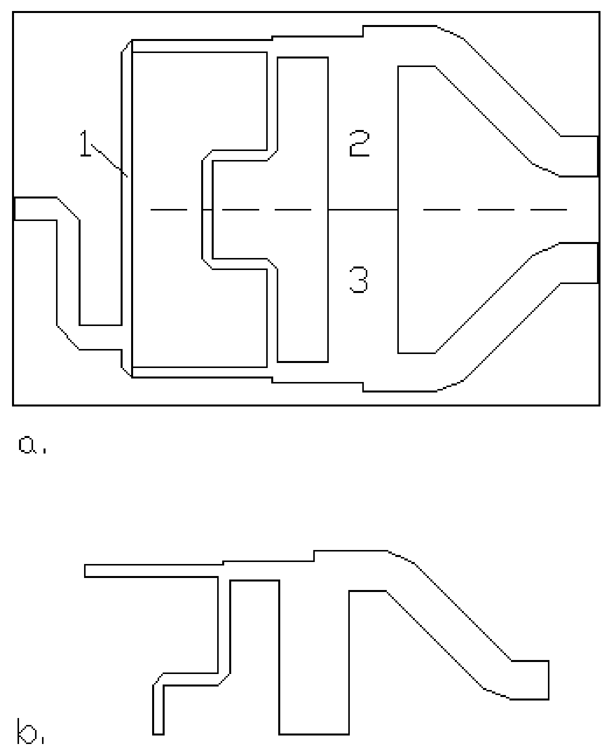

Fig.2: a) 2.1-3.6 GHz balun layout. b) Even-mode suppresser.

Fig. 2a shows the layout of the balun on a substrate with ε_r = 2.2 with a thickness of 0.8 mm. The overall dimensions of the substrate are 75 $\times$ 49 mm. The balun converts the impedance of 25Ω at each output into 50Ω at the input. Fig. 2a identifies the odd mode launcher (1) and the subsequent symmetric circuit with two parts (2 and 3) separated by the symmetry axis, indicated by a dashed line. Fig. 2b shows the equivalent even mode circuit, operating as a stopband filter.

Calculations indicate for the structure from Fig. 2a a return loss better than 20 dB and a ratio of the odd mode to even mode magnitude at the output exceeding 28 dB throughout the specified range.

Fig. 3 compares the calculated performance of the balun with the experimental results.

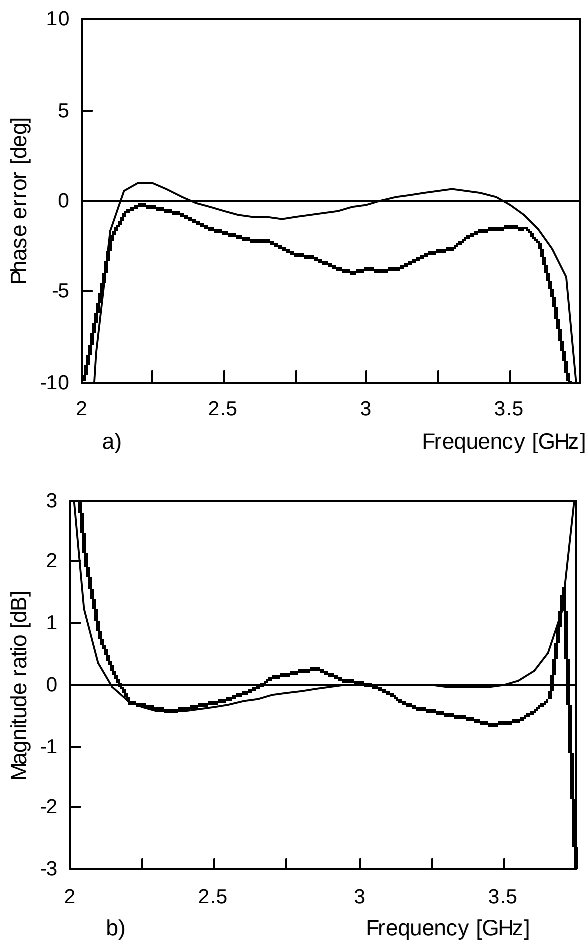

Fig. 3: Unbalance of the balun from Fig. 2a. Thin line: calculated; thick line: measured. a) Phase error b) Magnitude error.

For purposes of measurement by means of a network analyzer the balun was followed by a separate substrate with impedance transformers from 25Ω back to 50Ω and with coaxial-to-microstrip transitions. The non-identity of those elements and of the bondwires used between substrates may have contributed to the measured errors. Even so, the test results are in good concordance with the calculated data. The return loss was better than 20 dB over the entire band. Measurement of two baluns back-to-back yields an overall insertion loss of 0.6-0.8 dB, meaning for each balun a loss of about 0.3 dB over most of the range, increasing to 0.4 dB at the higher frequencies. This value includes the loss of the coaxial transition.

CONCLUSIONS

Obviously, the half-wavelength path difference is not the only conceivable elementary odd-mode launcher. Likewise, the performance enhancing symmetric network cascaded to it can present an endless variety of topologies. Understanding the distinction between the two parts can provide a basis for imaginative designs, as well as a tool for their adjustment. In particular, addition of series connected elements across the symmetry axis affects only the odd-mode, while shunt elements along this line affect exclusively the even-mode. With proper resistors used as such shunt elements, for example, isolation can be obtained between the antiphase outputs, if needed.

The rigorous planarity of this balun (no multiple layers, ground cavities, bondwires or via holes) makes it convenient for integration in a more complex microstrip network and translates into low cost. Besides, as frequency increases, departures from planarity would tend to act as parasytics, therefore their absence is favorable for extending the operation of the baluns described above towards higher frequencies.

REFERENCES

[1] Vendelin, G.D., Pavio, A.M., Rohde, U.L., “Microwave Circuit Design Using Linear and Nonlinear Techniques”, Wiley-Interscience, 1990

[2] Maas, S.A., “Microwave Mixers”, Artech House, Boston,London 1993.

0-7803-4471-5/98/$10.00 (c) 1998 IEEE