A Monolithic, Compact Balun/Matching Network for SiP Applications

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Abstract: *We describe a circuit and design method for a compact balun/matching network suitable for a variety of RF application using thin-film integrated passive device (IPD) technology. The circuit uses resonant coupled inductors. By appropriate tuning of the capacitors in the circuit, the balun can be made to match a wide range of impedances. Measured results of example circuits for 802.11b/g or Bluetooth applications (2.4-2.5GHz) are presented, showing excellent agreement with simulation.*

1. Introduction

Balun transformers are widely used in RF systems to couple signals between balanced to unbalanced transmission lines. RF integrated circuits often use a balanced (i.e. differential) signal path. Among other benefits, this improves the circuit's immunity to common-mode noise in the power supply. Most circuit board elements, however, like antennas and filters, operate in a microstrip transmission line environment and use an unbalanced (i.e. single-ended) signal path. The purpose of the balun transformer is to couple the signal between these two transmission environments with minimal power loss.

Conventional discrete baluns are available with a variety of impedance ratios, typically for 50Ω unbalanced to an integer multiple of 50Ω balanced. Because RF ICs typically have arbitrary (and complex) impedance characteristics, it is necessary to insert a matching network between the chip and the balun to obtain an optimal power match. Although it is possible to use active circuits to make baluns and matching networks, the noise and limited linearity of active components usually rule out this approach. The insertion loss of passive baluns and matching networks (one of their main figures of merit) is directly related to component Q. The resistive losses in on-chip components are too high to be useful in most applications. Consequently, baluns and matching networks are usually external to the chip. Recently, however, there is a growing trend toward system-in-package (SiP) technologies that incorporate one or more chips along with associated passive components in a single package. This offers the advantages of reduced size and part count. This paper examines the design and characteristics of a monolithic balun/matching network circuit that is suitable for SiP.

Traditional Marchand and double-Y baluns use resonant quarter-wavelength sections of coupled transmission line. However, most telecommunications and wireless data applications are at frequencies below 5GHz where these types of baluns are too large to be practical for SiP. A modified Marchand-type balun using a compact spiral configuration has been reported.[1] This circumvents some of the size problems associated with such baluns, but is restricted to a very specific impedance ratio. A more general balun type for monolithic technologies uses a network of lumped inductors and capacitors, making it more suitable for a range of impedances.[2] Circuits of this type can be used to match over a wider variety of impedances, but have limited bandwidth and are particularly sensitive to process-induced variations in component value.

In the following sections, we describe a balun that uses a resonant coupled-inductor pair. The circuit is compact, and has the advantage of incorporating both the balun and the matching network. It is not restricted to real impedances, and with suitable choice of inductor can result in very wide band performance.

2. Circuit Description

Figure 1 shows a transformer-based balun. Baluns of this type are commonly used in low frequency applications. The turns ratio determines the impedance transformation, and the center-tap on the balanced side of the transformer provides the common-mode reference. (Baluns are sometimes used to provide dc bias to the balanced terminals.) Note that baluns of this type are only suitable for matching real port impedances.

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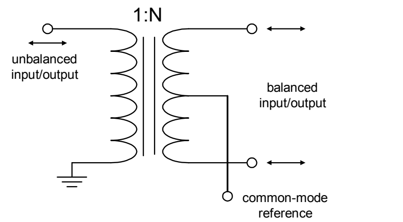

Figure 1: Transformer-based balun

The monolithic counterpart to the transformer is the coupled-inductor pair.[3] An ideal transformer is the same as a coupled inductor in the limit of infinite inductance and unity coupling coefficient. Since these limits are not attainable (even approximately) in practice, it is necessary to add capacitors to the circuit. By suitably adding resonance to the inductor pair, the overall reactive impedance can be made large enough so that the coupled inductor pair behaves like an ideal transformer over a limited bandwidth.

Figure 2a shows the symmetric (1:1) coupled inductor pair, which is the basic building block of the balun. An equivalent circuit is shown in Figure 2b. The relationship between the coupled inductor and the ideal transformer is apparent in this circuit. There is a finite inductance in shunt with the transformer (called the "core inductance" in conventional transformer analysis) that limits its low-frequency operation. Also, for coupling coefficient, k, less than unity, there are series inductances in the leads of the transformer (called "leakage inductance") that limit its high frequency performance.

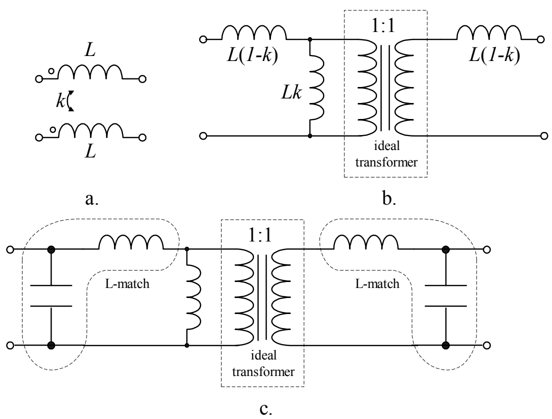

Figure 2: a) basic coupled inductor , b) equivalent circuit, and c) coupled inductor with shunt resonating capacitors, showing L-match elements.

By adding shunt capacitors to the inductor pair, as shown in Figure 2c, it is possible to resonate with the inductive elements of the couple to modify its characteristics. In particular, as emphasized in the figure, shunt capacitor elements act with the non-ideal leakage inductances to form L-match elements commonly used in matching networks. Other arrangements of capacitors are also possible. The key point of this figure is to illustrate that the inherent inductance of the coupled pair can be used together with added capacitors to obtain both transformer isolation and impedance transformation.

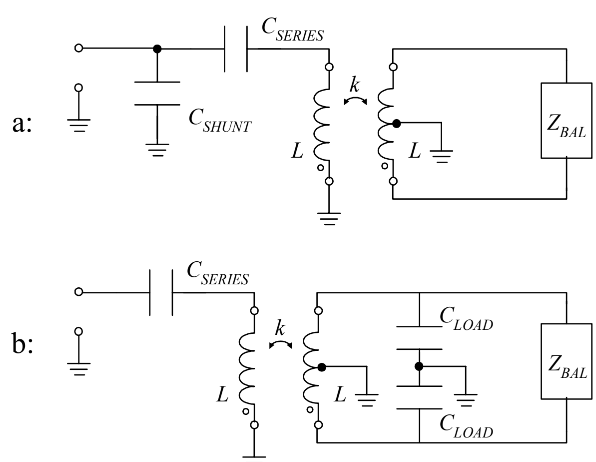

Figure 3: Two balun/matching network circuits.

Figure 3 shows the balun circuits used in this investigation. To match the real and imaginary part of an arbitrary load impedance requires two tunable elements. The circuit in Figure 3a uses two capacitors on the unbalanced side of the balun. In the circuit of Figure 3b, the shunt capacitor is replaced by a pair (to maintain balance) of capacitors on the balanced side. Note that the center-tap in both circuits can be used to supply common-mode bias to the balanced load.

Figure 4 shows the layouts of 5 balun designs. All of these baluns are designed to operate at a center frequency of 2.45 GHz for 802.11b/g and Bluetooth applications, and are designed for transformation from 50Ω unbalanced to 100Ω balanced impedance. The three pads on the bottom are for a ground-signal-ground coplanar probe (the unbalanced port, designated port-1) and the two sets at the top are for two similar probes (ports 2 and 3) that constitute the balanced terminals of the balun.

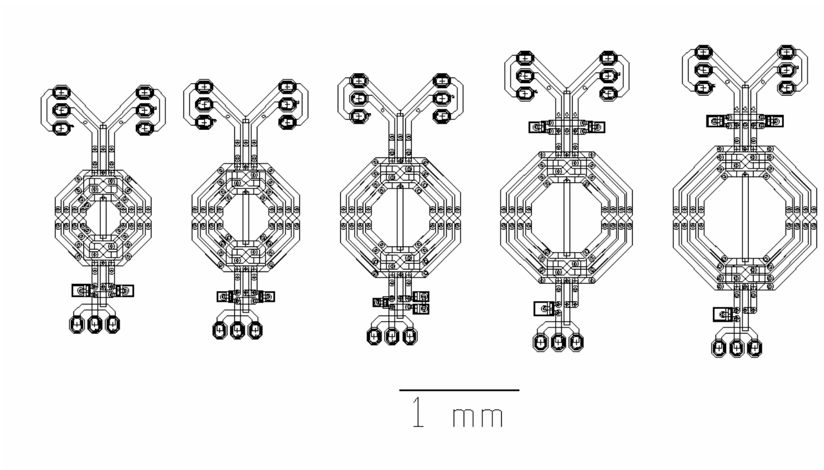

Figure 4: Balun designs.

The design procedure for the baluns was to first use electromagnetic simulation to determine the characteristics of the coupled inductors.[4] These were placed in a circuit simulator, and optimization was used to tune the values of the capacitors. Final verification of the circuit was done with EM simulation of the full layout.

The simulated characteristics of the baluns and the value of the components in the matching networks are listed in Table 1. (Baluns 1 through 5 correspond to the designs from left to right in Figure 4.) Note that for this sequence of inductors and port impedances, it was necessary to use the two different circuit architectures shown in Figure 3. The last two columns in the table list the simulated characteristics. The definition of bandwidth for a balun is somewhat arbitrary. In this case, it is determined by the frequencies at which the insertion loss is 0.5dB in excess of that at the band center. Note the dramatic increase in balun bandwidth for the larger inductors.

Table 1: Balun / matching network designs and simulated characteristics.

	Inductor		Matching network			Simulated characteristics	
Circuit	***L* (nH)**	**k**	**C_{SHUNT} (pF)**	**C_{SERIES} (pF)**	**C_{LOAD} (pF)**	**Loss (dB)**	**$BW_{0.5dB}$ (MHz)**
Balun 1	2.8	0.57	2.4	2.5	--	1.54	340
Balun 2	3.9	0.55	1.6	1.6	--	0.82	430
Balun 3	4.9	0.55	0.8	1.1	--	0.60	570
Balun 4	5.8	0.57	--	3.4	1.0	0.56	1500
Balun 5	6.7	0.59	--	3.2	1.0	0.62	1630

3. Experimental Results

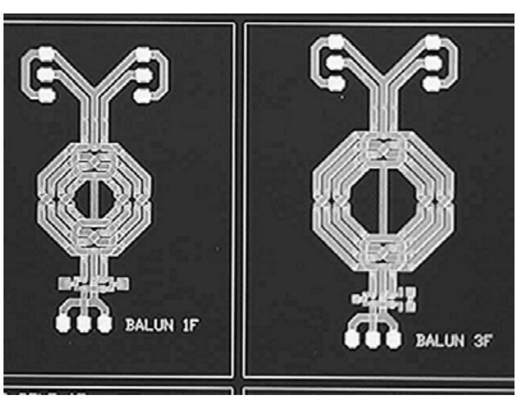

Figure 5: Micrographs of baluns 1 and 3.

Figure 5 shows a micrograph of two of the baluns. The baluns were fabricated on a specially prepared silicon substrate. The inductor coils are formed with two layers of 3 μm thick aluminum, and the capacitors (the small rectangular features below the inductor coils) are made with silicon nitride dielectric.

Figure 6 compares the S-parameters for balun-1 and balun-5. The S-parameters for the three-port networks were measured by a sequence of 2-port measurements, and the data renormalized to account for non-ideal loads on the idle port.[5] Note that the agreement with simulation is very good. Also apparent in these figures is the difference in bandwidth between these two designs. (The high bandwidth of the balun-5 design is obtained at the expense of greater area. Also, depending on the application, a smaller bandwidth may be more desirable.)

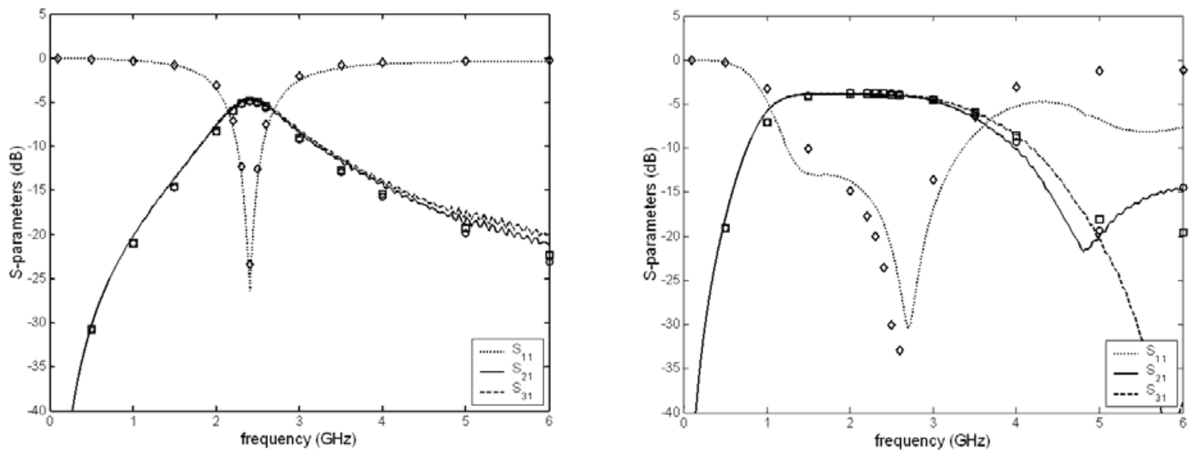

Figure 6 Measured and simulated S-parameters for balun-1 (left) and balun-5 (right). Port-1 is the unbalanced port and ports 2 and 3 constitute the balanced port.

4. General Use in SiP Applications

The choice of port impedance for these balun designs was chosen for ease of measurement with 50Ω equipment. In the more general case, the port impedance on the balanced side (the input or output of a chip) is complex. The methodology described in this investigation works equally well for arbitrary balanced port impedance. Exhaustive examination of the general case is impractical, since it depends on the operating frequency, desired bandwidth and the parasitic circuit elements introduced by the technology. In the particular case of 802.11 applications around 2.5GHz and for inductors in the range described above, it appears that this approach is practical for balanced loads with a real part between 20 and 500Ω, and a reactive part between +/-200Ω. This range would cover most applications.

A key advantage of circuits of this type in SiP applications, in contrast to conventional baluns, is that they can be custom built for the application. Consequently, they do not need to be made to a limited, predetermined set of port impedances. This makes it possible to combine the functions of balun and matching network into a single design. This not only reduces the size and cost of the overall circuit, but also improves the insertion loss compared with separate circuits.

Acknowledgements

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References

[1] Y. J. Yoon, Y. Lu, R. C. Frye, M. Y. Lau, P. R. Smith, L. Ahlquist, and D. P. Kossives, "Design and Characterization of Multilayer Spiral Transmission Line Baluns," IEEE Trans. Microwave Theory and Techniques, 1841-47, **47** 1999.

[2] D. Lew, J.-S. Park, D. Ahn, N.-K. Kang, C. Yew and J.-B. Lim, " A design of the Ceramic Chip Balun Using the Multilayer Configuration," ," IEEE Trans. Microwave Theory and Techniques,, 220-224 **49** (2001).

[3] J. R. Long, "Monolithic Transformers for Silicon RF IC Design," IEEE J. Solid State Circuits, 1368-1382, **35**, (2000).

[4] S. Kapur and D. Long, "Large-Scale Full-Wave Simulation," Proc. 41st Design Automation Conference, 806-809, San Diego, CA, June 7-11, 2004.

[5] J. Tippet and R. Speciale, "A Rigorous Technique for Measuring the Scattering Matrix of a Multiport Device with a 2-Port Network Analyzer," IEEE Trans. Microwave Theory and Techniques, 661-666, **30** 1982.