BALUN
BASICS
PRIMER

A Tutorial on Baluns, Balun Transformers, Magic-Ts, and 180° Hybrids

By: Doug Jorgesen and Christopher Marki

INTRODUCTION

The balun has a long and illustrious history, first documented in the literature as a device to feed the television transmitting antenna for the Empire State Building[1] in 1939. Since then designs have evolved dramatically, and applications have evolved beyond driving differential antennas to include balanced mixers, amplifiers, and signaling lines of all types. Baluns have long been ubiquitous in low frequency audio, video, and antenna driving applications. The need for high speed, low noise data transfer has driven the advancement of the balun to higher frequencies and superior performance.

Despite these advancements, information about baluns remains scattered and confusing; this application note seeks to resolve this problem by clarifying the basic characteristics of baluns. First we will define what a balun is, what it does, and how it is different from other components. Next we will define generic balun specs, which we then use to discuss the different types of baluns and their properties. Finally we will discuss the applications of baluns and how to determine what kind of balun is required for several different purposes.

I. WHAT IS A BALUN?

A balun is any three port device with a matched input and differential outputs. It is most succinctly described by the required (ideal) S-parameters:

$$S_{12} = -S_{13} = S_{21} = -S_{31}$$
$$S_{11} = -\infty$$

Note what is implied by this:

- A balun is a three port power splitter, similar to a Wilkinson or resistive power divider.
- The two outputs will be equal and opposite.
  - In frequency domain this means the outputs have a 180° phase shift.
  - In time domain this means the voltage of one balanced output is the negative of the other balanced output.
- The unbalanced input is matched to the input transmission line impedance (usually 50 Ω).
- Unlike an isolator or circulator, a balun is a reciprocal device that can be used bidirectionally.

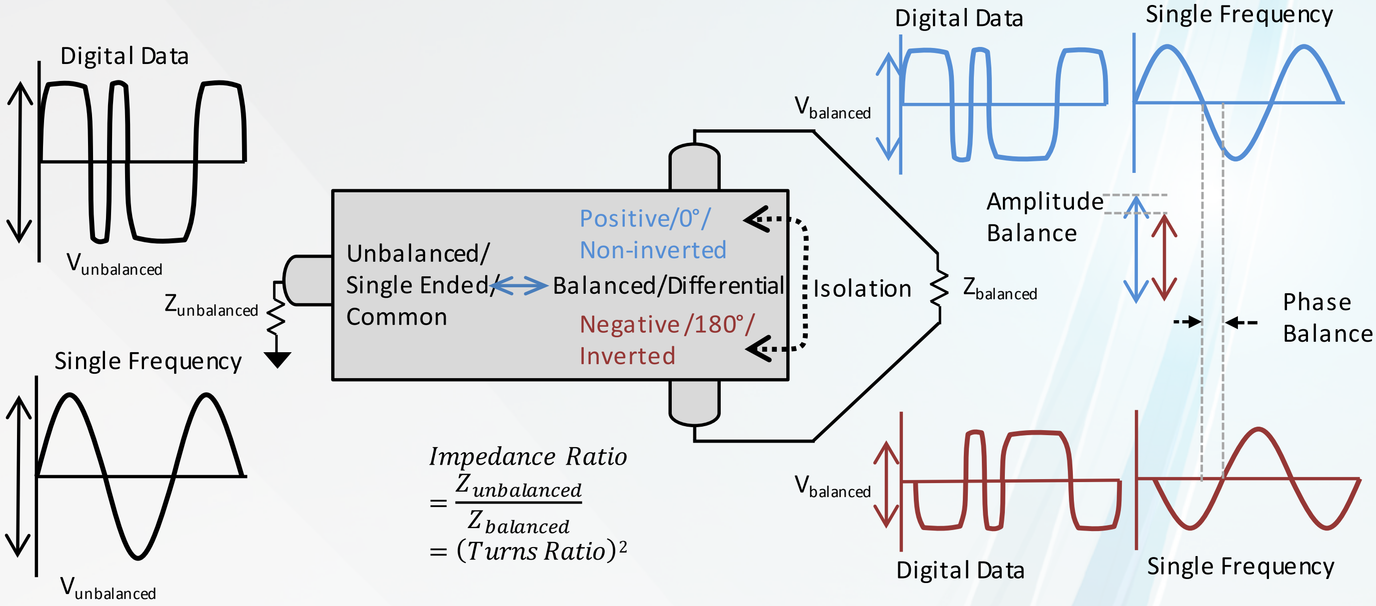

Fig. 1: Baluns convert between unbalanced and balanced signals

Also note what is not implied by this:

- The two outputs are not necessarily matched.
- The outputs of the balun may or may not be the same impedance as the input.
- There is no constraint on S_{23}, so the outputs may or may not have isolation.
- Therefore there may be a different return loss on the outputs for differential and common mode signals.

The term balun is a portmanteau of balanced and unbalanced, indicating that a balun will transition between a balanced (also called 'differential') transmission line (where opposite currents both travel in transmission lines) and an unbalanced (also called 'single ended') transmission line (where the return current travels in the ground). However, this description obscures the simplicity of the balun. A balun has equal power outputs just like a Wilkinson power divider, resistive power divider, or quadrature hybrid coupler. However, it has a 180° phase difference between outputs, while the power dividers have 0° phase difference and quad hybrids have 90° phase difference.

At low frequencies, the terms balun and transformer are often used interchangeably because low frequency baluns are almost always implemented using flux coupled transformers. For this reason it is often said that a balun is a type of transformer, but it is more accurate to say that a transformer can sometimes be used to implement a balun. Many other structures can also be used to implement balun functionality, as we will discuss in section IV. Before discussing the virtues of different types of balun structures, we need to define what performance specs are important for baluns.

II. BALUN PERFORMANCE SPECS

Frequency coverage: As with all RF/microwave circuits, each performance metric is only valid across some specified bandwidth. Increasing the bandwidth from octave, to decade, to multi-decade without sacrificing performance is a major challenge. In general Marki baluns can be divided into two types. Those with magnetic coupling perform below 10 MHz, while those with only capacitive coupling have low end performance limited to about 1 GHz, but can operate up to millimeter wave frequencies.

Phase Balance: The most important performance criterion is how close the balanced outputs are to having equal power and 180° phase, called balance. Phase balance is the measure of how closely the inverted output is to 180° out of phase with the non-inverted output, usually given in degrees. It is the most critical parameter for many balun applications. In addition to the quality of the balun structure, how closely matched the lengths of the output lines are determines the balance. Typical phase balance for standard microwave baluns is ±15° max and ±10° typical, while high performance Marki baluns approach ±5° max and ±2° typical.

Amplitude Balance: Related to phase balance, amplitude balance is also determined by construction and line matching. Although it is called amplitude balance, it is usually specified in dB and actually gives the match between output power magnitude. Low performance baluns have amplitude balance of ±1.5 dB max and ±1 dB typical, while Marki products approach ±.5 dB max and ±.2 dB typical.

Common Mode Rejection Ratio: If two identical signals with identical phase are injected into the balanced ports of the balun (called 'common mode' or 'even mode' signals), they will be either reflected or absorbed. The amount of attenuation this signal will experience from the balanced to unbalanced port is called common mode rejection ratio (CMRR) and is expressed in dB. It is determined by the vectorial addition of the two signals, and therefore is dependent on the amplitude and phase balance of the balun. The relationship between amplitude balance, phase balance, and CMRR is shown in Fig. 2. As a rule of thumb, a 0.1 dB improvement in amplitude balance will improve the CMRR by the same amount as a 1° improvement in phase balance. A low performance balun will have 15-20 dB of CMRR, while Marki baluns can achieve 25-55 dB of CMRR.

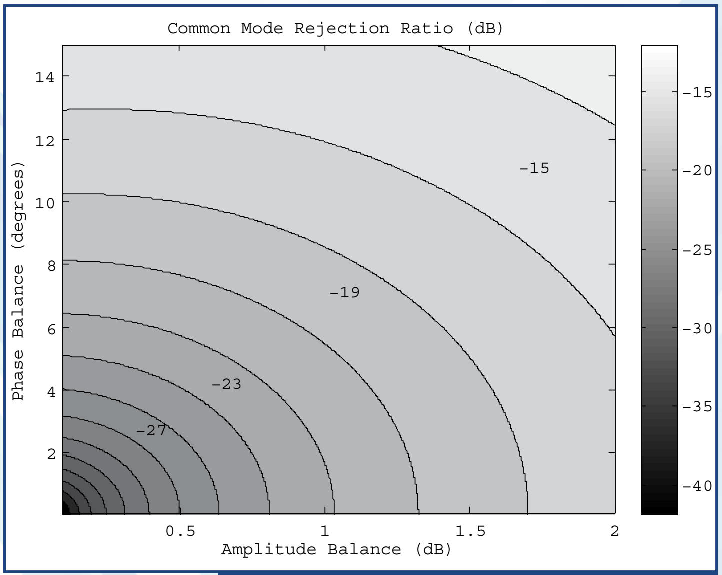

Fig. 2 Common Mode Rejection Ratio (in dB) as a function of amplitude and phase balance

Impedance Ratio/Turns Ratio: While the unbalanced impedance of a balun is matched to the input transmission line, the balanced impedance can be any value. The ratio of the unbalanced impedance to the balanced impedance is the impedance ratio, and is usually stated as 1:n (i.e. 1:1, 1:2, 1:4). Note that the differential impedance is between the balanced signal lines. This is twice the impedance between the signals and ground. A related value is the turns ratio, which for a flux coupled balun transformer is the ratio of primary windings to secondary windings. The impedance ratio is the square of the turns ratio (i.e. a 1:2 turn ratio gives a 1:4 impedance ratio). A higher output impedance will provide increased voltage at a reduced current, which is desireable for matching into high impedance semiconductor devices. High impedance ratio baluns are easy to design using flux coupled transformers, but much more difficult for transmission line transformers and other high frequency constructions.

Insertion and Return Loss: A lower insertion loss and higher return loss will mean more power available for downstream functions, an improved dynamic range, and less distortion of signals in previous stages of the system. In a balun without isolation, as in a reactive splitter, the return loss of balanced ports will be different for common mode and differential mode signals. In an ideal balun without isolation, the common mode signal would be perfectly reflected, with a return loss of 0 dB, while the differential signal would pass through completely with a return loss of -∞. To properly characterize this effect one can use mixed-mode S-Parameters instead of standard S parameters to determine how the device will operate with differential inputs[2].

Balanced Port Isolation: Usually referred to simply as isolation, this has the same meaning as in other power dividers and couplers, namely the insertion loss from one balanced port to the other in dB. Most baluns do not offer high isolation because the even mode is reflected instead of being properly terminated with a resistive load. The exception is 180° hybrid circuits, where the even mode is output to a port that can be resistively terminated.

DC/Ground Isolation: Different from the balanced port isolation, DC isolation is whether the unbalanced port has a DC connection to one of the balanced ports. Ground isolation is whether there is a connection between the unbalanced ground and the balanced signals or grounds.

Group Delay Flatness: For data transmission applications, a flat group delay will ensure a minimal amount of distortion. Group delay flatness is the difference from the average delay across frequencies. This parameter can most easily be evaluated by either measuring directly on a VNA or examining the output eye diagrams from an input amplitude shift keyed signal. Unwanted group delay ripple is related to poor broadband matching. Baluns with superior return loss will have superior group delay flatness.

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