

RF Transformers

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Demystifying RF Transformers: A Primer on the Theory, Technologies and Applications (Part 1)

In essence, a transformer is merely two or more conductive paths linked by a mutual magnetic field. When a varying magnetic flux is developed within a core, by alternating current passing through one conductive path, a current is induced in the other conductive paths. This induced current is proportional to the ratio of the magnetic coupling between the two conductive paths. The ratio of the magnetic coupling of the conductive paths with the core determines the induced voltage in the additional conductive paths, providing both an impedance transformation and a voltage step-up or step-down. Additional conductive paths, potentially all with different coupling ratios, may be added to realize various functions, which is why RF transformers are such varied and versatile devices and used widely throughout the RF/microwave industry.

A common implementation of an RF transformer consists of two or more distinct wires wrapped around a magnetic core - or an air core at higher frequencies - which is why RF transformers are often described as the ratio of the number of windings or turns. RF transformers are used for a variety of applications, as the nature of the device allows for various configurations serving different functions, including:

- Providing an impedance transformation for impedance matching.
- Stepping up or down a voltage or current.
- Efficiently coupling between balanced and unbalanced circuits.
- Enhancing common mode rejection.
- Providing DC isolation between circuits.
- Injecting DC current.

Several common technologies are used to build transformers, including core-and-wire, transmission line, low temperature co-fired ceramic (LTCC) and MMIC. Each is available in a variety of packages with a range of performance characteristics.

Transformer Theory

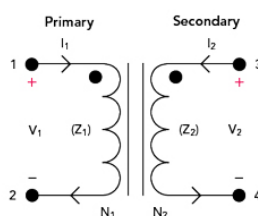


Figure 1 - Schematic of an ideal transformer.

Though not realistic for actual applications, a model of the ideal transformer illustrates the fundamental behavior of transformers (see **Figure 1**). Ports 1 and 2 are the input of the primary winding, and ports 3 and 4 are the output of the secondary winding. From Faraday's Law, the current through the primary winding creates a magnetic flux through the mutual magnetic field of the core, inducing a proportional current and voltage in the secondary winding. Both the current and voltage developed are proportional to the ratio of the windings or the magnetic coupling between the windings and the core. Hence, the secondary impedance is a function of the square of the windings ratio multiplied by the impedance of the primary. The operation is described by the following:

$$n = \frac{N_2}{N_1}, V_2 = nV_1, I_2 = \frac{I_1}{n},$$

$$Z_1 = \frac{V_1}{I_1}, Z_2 = \frac{V_2}{I_2}, Z_2 = n^2 Z_1 \quad (1)$$

where I_1 , V_1 and Z_1 are the current, voltage and impedance through the primary winding; I_2 , V_2 and Z_2 are the current, voltage and impedance through the secondary winding; N_1 is the number of turns in the primary winding; and N_2 is the number of turns in the secondary winding.

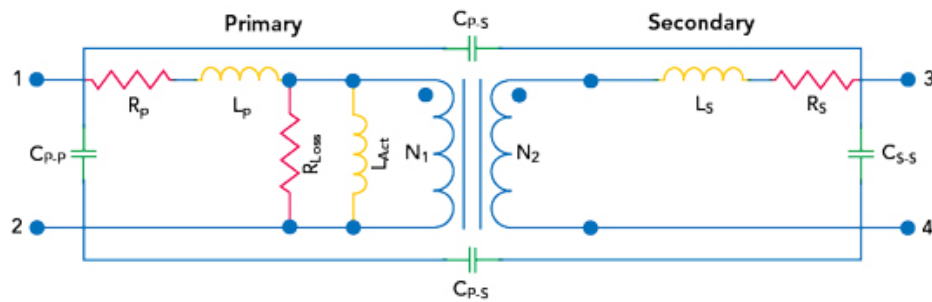


Figure 2 - Transformer model with parasitic elements.

A real transformer includes several parasitic resistances, inductances and capacitances, both mutual and self-parasitic capacitances. **Figure 2** shows a lumped-element model of a non-ideal RF transformer, which depicts the parasitic resistances and inductances of the two windings, as well as the core resistive losses and the windings' active inductance. The parasitics cause an actual transformer to operate over a limited bandwidth, with insertion loss and limited power handling (see **Figure 3**). The performance also depends on frequency, temperature and power.

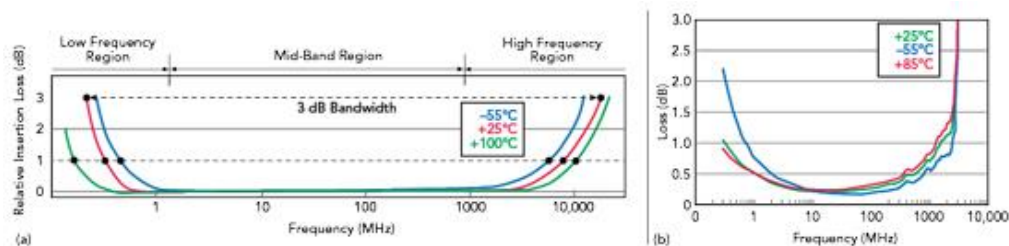


Figure 3-Theoretically, a transformer has a bandpass frequency response (a) which measurements confirm (b).

An actual RF transformer's lower cutoff frequency is dictated by the winding's active inductance, and the high frequency cutoff is dominated by the inter-winding and intra-winding capacitance. The insertion loss in the operating bandwidth is a product of the ohmic losses in the primary and secondary windings, as well as the dissipation within the core. As the ohmic losses tend to be a function of frequency and temperature, the transformer's effective operating bandwidth is limited by these factors. Several RF transformer types introduce leakage inductances due to incomplete magnetic coupling between the windings. As the reactance of the leakage inductance is proportional to frequency, these parasitics reduce the return loss at high frequency and increase the insertion loss at lower frequency.

More complex RF transformer topologies, such as transformers with several windings, taps and additional elements, present varying performance dynamics based on the topology and transformer construction. For example, an RF device known as a balun is used to efficiently interconnect balanced (i.e., differential signal) circuits to unbalanced (i.e., single-ended signal) circuits using impedance transformation; it can be realized with an RF transformer. Another device similar to a balun, known as an unun, is used to interconnect unbalanced to unbalanced RF circuits, and it can be realized with an RF transformer. A common balun fashioned from a transformer is a flux coupled balun transformer, constructed by winding separate wires around a magnetic core and grounding one side of the primary winding. The single-ended RF signals entering the primary unbalanced winding undergo an impedance transformation to a differential (i.e., balanced) output through the secondary winding.

RF transformers that include a magnetic core - typically ferromagnets - have several undesirable factors that degrade performance. The magnetizing inductance of the core limits the low frequency performance of the transformer. This inductance is a function of the core permeability, cross sectional area and number of windings around the core. The magnetizing inductance increases the insertion loss at low frequencies and degrades the return loss. The permeability of the core is also a function of temperature; permeability increasing with temperature increases the low frequency insertion loss.

RF Transformer Technologies

The two main types of discrete RF transformers are core-and-wire and transmission line. Additionally, two common types of low profile and compact transformer designs are LTCC and MMIC.

Core-and-Wire RF Transformers



Figure 4 - Construction of a wire-wound transformer with magnetic core.

Core-and-wire transformers are fabricated by wrapping conductive wires, typically insulated copper wires, around a magnetic core such as a toroid. There may be one or more secondary windings, which may also be center tapped to enable additional functions. **Figure 4** shows an RF transformer made from a toroidal magnetic core and insulated copper windings. Due to the nature of the inductive coupling between the wires and the core, smaller core-and-wire dimensions tend to yield core-and-wire transformers that operate at much higher frequencies than those with larger core-and-wire transformers. However, the smaller size of the compact transformers increases the resistive losses of the windings and the core, resulting in greater insertion loss at lower frequencies.

Transmission Line RF Transformers

Transmission line transformer topologies may include precisely designed transmission lines placed between two mismatched loads or a complex arrangement of several transmission lines. For instance, a length of transmission line can be used to implement an impedance transformation between two mismatched loads. Some transmission line transformers use insulated wires wrapped around ferrite cores, closely resembling typical core-and-wire transformers - often considered core-and-wire transformers. Nonetheless, the following discussion is provided less for categorization than to describe transformer behavior and enhance understanding.

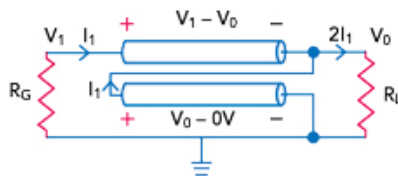


Figure 5 - Schematic of an ideal transmission line transformer.

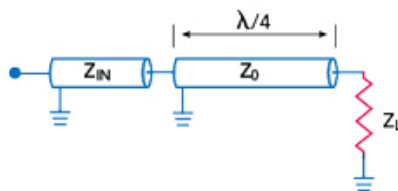


Figure 6 - Quarter-wave transmission line transformer.



Figure 7 - Transformer fabricated with LTCC technology.



Figure 8 - Transformer fabricated with MMIC technology.

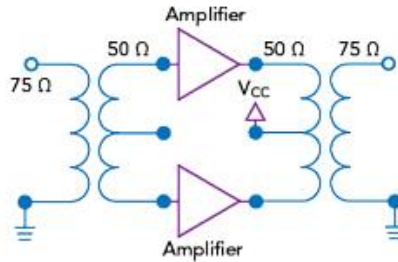


Figure 9 50 Ω balanced amplifier using transformers for impedance matching to 75 Ω.

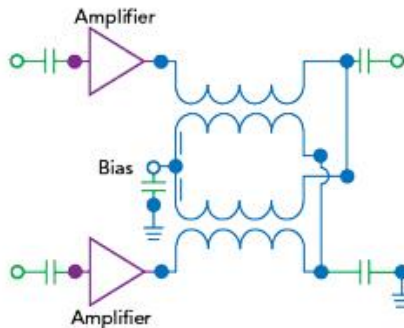


Figure 10 - Using a center-tapped transformer to replace bias tees.

A basic transmission line transformer consists of a two conductor transmission line. The first conductor is connected from the generator to the load, and the other conductor is connected at the output of the first transmission line and the load to ground (see **Figure 5**). With this configuration, the current flowing through the load is twice the current flowing through the generator, and V_0 is half the voltage V_1 . Hence, the load resistance is only a quarter of the resistance seen at the generator side, yielding a 1:4 transformer, as described by

$$\begin{aligned} V_0 &= \frac{V_1}{2}, R_G = \frac{V_1}{I_1}, \\ R_L &= \frac{V_0}{2I_1} = \frac{V_1 / 2}{2I_1} = \frac{R_G}{4} \end{aligned} \quad (2)$$

A common version of the transmission line transformer is the quarter-wave transmission line. This topology uses a transmission line with a characteristic impedance that enables impedance matching between the input impedance and the load. The length of a quarter-wave transformer is dictated by the operating frequency, with the bandwidth limited to one octave around the center frequency.

Consider a lossless transmission line with characteristic impedance Z_0 and length L , connected between an input impedance Z_{in} and load impedance, Z_L (see **Figure 6**). To match Z_{in} with Z_L , the characteristic impedance of the quarter-wave transmission line, Z_0 , is determined by

$$\beta = \frac{2\pi}{\lambda}, Z_{IN} = Z_0 \frac{Z_L + jZ_0 \tan \beta L}{Z_0 + jZ_L \tan \beta L}$$

$$@L \sim \frac{\lambda}{4} Z_{IN} = \frac{Z_0^2}{Z_L}, Z_0 = \sqrt{Z_{IN} Z_L} \quad (3)$$

One advantage of a transmission line transformer is that a significant portion of the interwinding capacitance, along with the leakage inductance, is assumed by the transmission line, which results in a wider operating bandwidth compared to core-and-wire transformers.

LTCC Transformers

LTCC transformers are multilayer components fabricated using a ceramic-based substrate. LTCC transformers use coupled lines acting as transmission lines to achieve impedance transformation and signal conversion from single-ended to balanced. LTCC transformers rely on capacitive coupling, enabling LTCC transformers to operate at higher frequencies compared to ferromagnetic transformers. However, this may lead to performance degradation at low frequencies. One benefit of LTCC technology is the ability to fabricate small and rugged transformers, ideal for high-reliability applications (see **Figure 7**).

MMIC Transformers

Like LTCC transformers, MMIC transformers are made using 2D substrates with precision layered planar metallization. Typically, MMIC transformers are fabricated using spiral inductors printed on a substrate in a two-transmission line configuration, with the lines parallel. A MMIC transformer can be fabricated using a GaAs integrated passive device process (see **Figure 8**). The precision lithography helps achieve outstanding repeatability, high frequency performance and excellent thermal efficiency.

Transformer Functions & Applications

Depending upon topology, RF transformers serve a variety of functions:

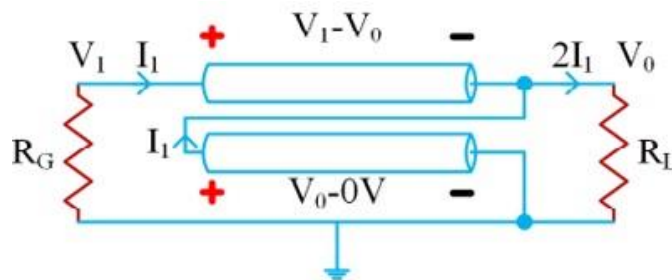
- **Matching** - A transformer can match two circuits with different impedances or provide voltage step-up or step-down of the source voltage. In RF circuits, an impedance mismatch between two nodes causes reduced power transfer and troublesome reflections. The impedance matching transformer effectively eliminates the reflections and provides maximum power transfer between the two circuit nodes (see **Figure 9**).

- **Baluns and Ununs** - Baluns are used to connect balanced and unbalanced circuit sections. For unbalanced lines, an auto-transformer configuration can be used for impedance matching, i.e., an unun.
- **Bias injection and isolation** - An RF transformer can be designed to provide DC isolation between the primary and secondary windings, which is useful for separating RF circuits requiring a DC bias from circuits negatively impacted by a DC voltage. If a DC current is required for a portion of the circuit, a specialized RF transformer can be used to inject current into the signal path. For example, two center-tapped transformers can inject a DC bias and replace two bias tees (see **Figure 10**).
- **Other functions** - RF transformer designs can be used to provide enhanced common mode rejection for balanced (i.e., differential) circuits. Other topologies can function as a choke, filtering high frequency components from a signal line.

Summary

RF transformers are fabricated using a wide variety of manufacturing methods and diverse materials. They are configured in a myriad of topologies to perform many functions in RF circuits. Depending on the materials, construction and design, RF transformers can be narrowband or wideband, operating at low or high frequencies. Understanding the nuances of RF transformers can help designers optimize a design by choosing the best transformer. Additional articles discussing RF transformers will be published online at www.mwjjournal.com.

Part 2: Baluns & Ununs



Introduction

Baluns and Ununs are essential in RF signal chains for many applications. RF balun designs are most commonly associated with core-and-wire transformers, but can also be realized through coaxial and coupled stripline technologies. The behavior of baluns and ununs was introduced in Part 1 of this series, where we established that both these devices are designed for impedance matching purposes. The major difference between them is that baluns are designed to match impedances between balanced and unbalanced circuits, whereas ununs provide impedance matching between two unbalanced circuits.

Part 1 of our Demystifying RF Transformers series discusses the basic theory and applications of RF transformers. This article aims to provide a deeper investigation into baluns and ununs with the main focus on baluns due to their greater prevalence in real-world applications.

Common Balun Applications

- The most common use for baluns is when a single-ended power amplifier is used to drive a balanced load. Examples include dipole antennas or single-ended antennas such as whips, which are needed to feed an additional front-end amplifier (see **Figure 1**). In the past, baluns were also widely used in the CATV industry, for example when matching between a 300Ω dipole antenna for broadcast TV with a 75Ω coaxial cable. With the development of RF Integrated Circuits (RFICs), baluns are now also widely used to improve noise immunity and common mode rejection. The growth in 5G applications has also led to tremendous demand for small, wideband baluns to interface with highly integrated radio transceivers using differential inputs and outputs.
- Ununs are often used if an unbalanced feedline is driving an unbalanced antenna, and there is an impedance mismatch between the feedline and the antenna. A whip antenna with a low input impedance would benefit from an impedance transforming unun to efficiently couple a 50Ω feedline with the antenna.

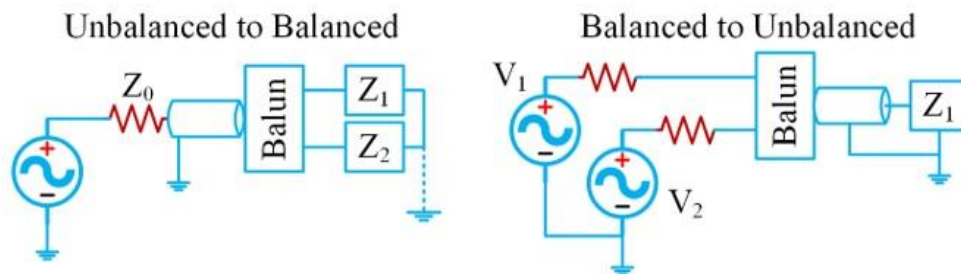


Figure 1: Unbalanced to balanced circuit conversion (left) and balanced to unbalanced circuit conversion (right).

Introduction to Balun Theory and Balanced and Unbalanced Systems

Before tackling balun theory, it is important to understand the differences between balanced and unbalanced two-terminal sources and loads. In a balanced circuit, signals travel along two paths, each with equal impedance to ground. The impedance of a balanced system is defined by the impedance between the two paths, whereas in an unbalanced system, one terminal is connected to ground.

Figure 2 illustrates the difference between signal response in a balanced and unbalanced circuit. The unbalanced circuit shows the voltage established between a single line and ground. The amount of current flowing between ground and the source is equal to the current in the circuit. The balanced circuit shows a differential signal flowing where the voltage is the potential difference between the two lines. In this case, the current flowing to ground on one line is equal to the current flowing from ground on the other line.

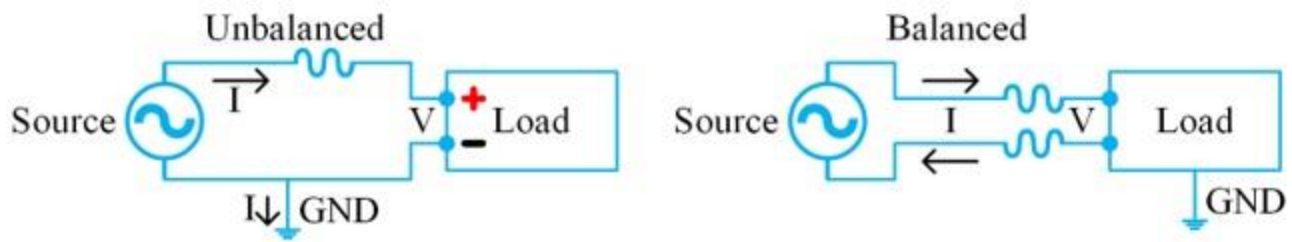


Figure 2: Unbalanced circuit (left) and balanced circuit (right)

Common Two-Terminal Systems:

- **RF Feedlines**
 - Coaxial cables (75Ω or 50Ω) unbalanced
 - High-speed data lines (100Ω or 120Ω)
 - Ladder lines (450Ω)
 - Open wire lines (600Ω)
- **Loads**
 - Receivers
 - Antennas during transmission
 - Meter or test instrument with a receiver
- **Signal Sources**
 - Antennas during reception
 - Transmitters
 - Signal generators
 - Meters or test instruments with a generator

Understanding the difference between common mode signals and differential signals is crucial for understanding the importance of baluns. In a balanced circuit, common mode signals are those that are equal in magnitude and polarity between the two lines. Differential signals, on the other hand, are equal in magnitude, but opposite in polarity. In general, differential signals are much more robust. This is due to the fact that differential signaling has inherent noise immunity. In a typical system, external noise is equally present on both lines of a balanced configuration and appear as a common mode signal. A differential signal is represented by the difference in voltage between the two lines. Since the common mode signal is equal on both lines, it is cancelled out.

Balun Modes & Technologies

There are two main modes of baluns: current baluns and voltage baluns (see **Figure 3**). Current baluns operate by forcing equal currents on both balanced lines, effectively eliminating common-mode currents. Voltage baluns force equal voltage on each balanced line; this is ultimately a better fit for impedance matching applications.

Like most transformers, baluns can be fabricated using core-and-wire transmission lines (e.g. coax), Low Temperature Co-fired Ceramic (LTCC), and Monolithic Microwave Integrated Circuit (MMIC) technologies. There are two main versions of core-and-wire baluns: isolation transformers and autotransformers, both of which are voltage baluns (see **Figure 4**). Above a few gigahertz, it is often necessary to use transmission line baluns to achieve desirable performance. One of the best-performing varieties of transmission line balun is the Marchand balun (see **Figure 5**). Many of Mini-Circuits' LTCC and MMIC baluns use the Marchand balun topology.

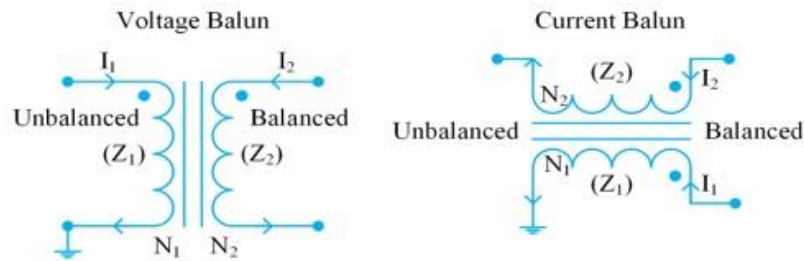


Figure 3: Voltage balun (left) and current balun (right).

Core-and-Wire Baluns (Isolation & Autotransformer Baluns)

Isolation balun transformers are RF transformers with the unbalanced side tied to ground and the balanced side connected to the load. Similarly to standard RF transformers, the ratio of windings can also be used to create an impedance transformation. Figure 4 illustrates an autotransformer balun with balanced inputs at either end of the winding, a center tap to ground, and one end of the winding creating the unbalanced port. One major benefit of this type of transformer is that the input and output are electrically separated, allowing a degree of protection for systems that are prone to ground loops in their ground-level voltages.

Autotransformers have a different configuration from that of typical RF transformers, since this topology has only a single conductive path. Autotransformer baluns can be fabricated by winding a single wire around a ferrite core, or by cross-wiring the primary and secondary windings. A tap point between the two ends of the winding is used to access different voltage potentials relative to the transformer input voltage. This configuration incorporates a DC current path to ground for each terminal, dissipating any static build-up.

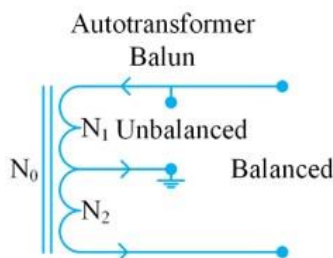


Figure 4: Diagram of an autotransformer balun.

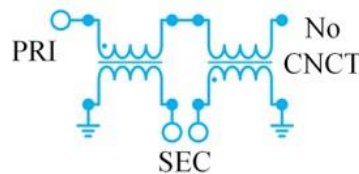


Figure 5: Diagram of a Marchand balun.

Transmission Line Baluns and Ununs

Transmission line balun transformers are typically constructed of a transmission line such as a coaxial cable wrapped around a ferrite core, and in some cases merely air. This 1:1 type of balun transformer creates a high choking reactance on the outer conductor of the coaxial cable, effectively reducing common-mode signals while allowing the internal currents of the coaxial transmission line to pass unimpeded (i.e. a Guanella Balun). Additionally, configurations include a bifilar capacitively coupled balun using two wires wrapped around each other as well as capacitively and magnetically coupled transmission lines wrapped around each other and then wrapped around a common core. The purpose of using a magnetic core with broadband transmission line couplers is to enable low frequency operation.

Broadband balun transformers are also constructed with various impedance transformations using several transmission lines in series and parallel arrangements. In this case, the impedance transformation is $1:n^2$, where n is the number of series-parallel transmission lines. Quarter-wave and half-wave transmission line balun transformers are also possible, although these types of baluns are best suited to applications with a narrow operating frequency range.

LTCC and MMIC Baluns

Balun production can also involve the use of planar metal structures with technologies such as LTCC and MMIC. This choice of design and fabrication is often proprietary. Generally, the main benefit of these designs is the small footprint that can be readily integrated into a microwave assembly. Unlike other baluns, LTCC- and MMIC-based baluns are produced using high-precision assembly machines and semiconductor manufacturing methods that yield much higher repeatability.

Key Balun Performance Parameters

Baluns share most of the same performance parameters as RF transformers, but the unique construction and use of baluns introduces additional considerations. These parameters include:

1. Phase balance
2. Amplitude balance
3. Common-mode rejection ratio
4. Balanced port isolation
5. DC/ground isolation
6. Group delay flatness

Phase & Amplitude Balance

Phase and amplitude balance (or unbalance) are a measure of how equal and opposite a balun's balanced output voltage and current are. In essence, any unbalance in a balanced line's voltage/current phase or amplitude yields additional losses and stray currents. Phase balance measures how closely the phase difference between the inverted input and non-inverted input are to an ideal 180° out of phase. The amplitude balance is the absolute value of the output power on each balanced line. For these parameters, each balanced line should be as close to equal as possible. The determining factors for phase and amplitude balance in real baluns include material properties, fabrication methods, and match between the output lines. Modern high-performance baluns are generally specified for no more than a few degrees of phase unbalance and a few dB of amplitude unbalance.

Common-Mode Rejection Ratio

The Common-Mode Rejection Ratio (CMRR) is a measure of how well common-mode signals are attenuated from the balanced port to the unbalanced port. This ratio is dependent on amplitude and phase unbalance. A balun with better amplitude and phase balance will also exhibit enhanced CMRR. A generally accepted guideline is that a 0.1 dB improvement in amplitude balance, or a 1 degree improvement in phase balance, will enhance the CMRR of a balun by roughly 1 dB.

Balanced Port Isolation & DC/Ground Isolation

Balanced port isolation is a measure of the ratio of input signal strength to output signal strength from one balanced port to another (insertion loss). More often than not, this parameter is not very high in most balun designs. DC isolation is a measure of the DC conductivity between the unbalanced port and balanced ports while ground isolation is a measure of the isolation between the unbalanced port ground and the ground (or pseudo ground) of the balanced ports. These isolation figures are important to determine a device's immunity to noise and interference. The isolation potential of a balun is often limited by the balun topology.

Group Delay Flatness

Group delay is the time it takes for the frequency components of a signal to pass through a device. The flatness of the group delay is a way to gauge the amount of distortion the broadband or high-speed signals will encounter passing through a device. It is generally desirable for every frequency component of a signal to pass simultaneously. In the case of a balun, good broadband matching is related to good group delay performance. Baluns with better return loss will typically demonstrate better group delay flatness.

Important Balun & Unun Applications

Baluns were originally used to provide impedance matching and to present balanced outputs to balanced antennas fed by unbalanced transmission lines. With the advent of solid state electronics, the outputs and inputs of many solid state devices (e.g. amplifiers, mixers, DACs/ADCs) present unbalanced ports. Though unbalanced outputs can readily be connected to common transmission lines such as coaxial cables, differential signaling lines are generally less susceptible to noise and crosstalk. Many of these lines are also less expensive than coaxial cables for long distance transmission.

For example, balancing push-pull amplifiers and mixers enables designs with reduced spurious content and enhanced CMRR, i.e. double-balanced mixers (see **Figures 6 and 7**). Note that the center taps on the baluns in Figure 7 are used for biasing the balanced amplifier. Another common application is the balancing and impedance matching of wideband converters to unbalanced sources, which generally exhibit port impedances that are very different from those of converter ports (see **Figure 8**).

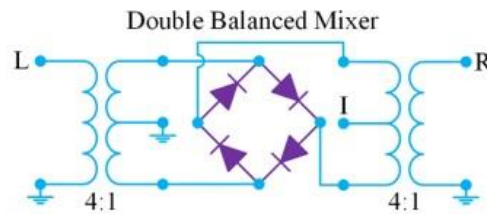


Figure 6: Double-balanced mixer using baluns on the input and output.

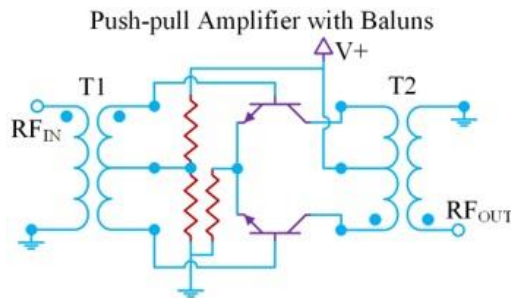


Figure 7: Balanced amplifier with baluns on the input and output.

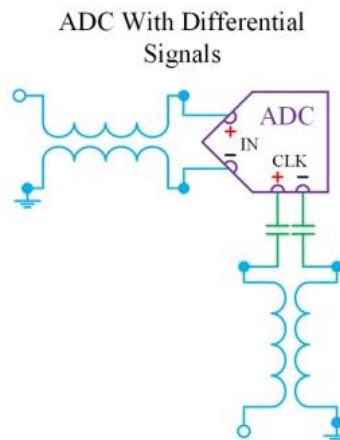
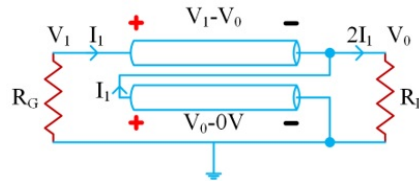


Figure 8: An ADC with differential input transformed into single-ended output.

Conclusion

Baluns have become highly useful devices that address many challenges of RF/microwave systems, transitioning unbalanced circuits (single-ended or ground referenced) to balanced circuits (full differential). Baluns also provide impedance matching between these circuits and enhance the CMRR of interconnect and devices. Baluns can be fabricated using a variety of technologies, including core-and-wire transformers, transmission line transformers, even low-profile, small-footprint LTCC and MMIC technologies.

Part 3: Understanding RF Transformer Parameters



Introduction

The first two sections of the Demystifying RF Transformers Series presented a basic overview of the theory and applications for RF transformers and a deeper discussion of RF baluns. This section provides an explanation of the predominant RF transformer performance parameters and data plots representing how these parameters are determined. An understanding of these key parameters is essential when selecting transformers for an application, as well as for comparing different transformer models.

Key RF Transformer Parameters

RF transformers are broadband devices with operating characteristics beyond a narrow set of frequencies. There are several regions where RF transformer performance versus frequency varies from the generally accepted or desired mode. For RF transformers, the desired operating region is called the mid-band region, which is defined by the transformer's behavior in the low frequency region and high frequency region. In some cases, however, an RF transformer may be used outside the mid-band region depending on design and application requirements. As such, there is sometimes confusion over the exact operating bandwidth for a give RF transformer, as well as the operating conditions under which the specifications of a transformer are derived.

This is why reading the performance plots swept over frequency and temperature is often helpful in determining these factors. One important facet of RF transformer performance presentation is that the insertion loss versus frequency response curves are often presented with a logarithmic scale for frequency and loss (attenuation). It is not uncommon for loss to be represented as a positive quantity, or attenuation presented as a negative value. Therefore, an RF transformer's loss versus frequency may appear as a bathtub curve or an inverted bathtub curve, depending on presentation (see Figure 1).

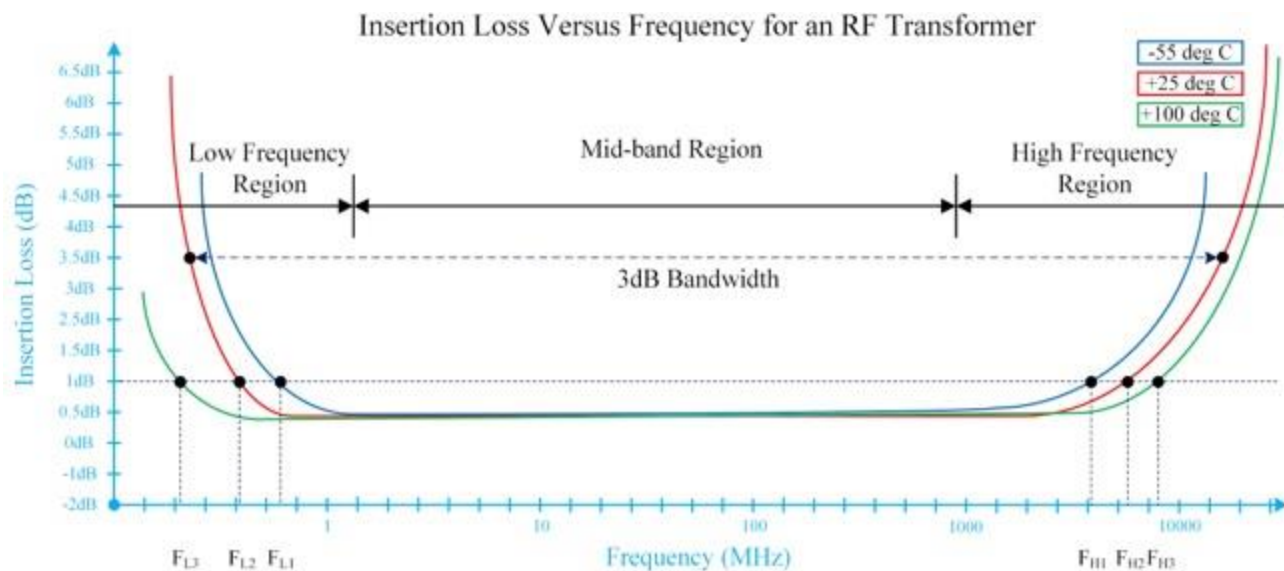


Figure 11: Average Insertion Loss of a Mini-Circuits TCM1-83X+ RF Transformer

Impedance Ratio

There are several methods of testing RF transformers. Mini-Circuits transformers are tested in balun configurations using a 50Ω impedance system. A Z-conversion (impedance conversion) is either applied to the network analyzer or to the data, using calculations to correct the transformer's impedance, be it 75Ω, 100Ω, etc. this is done with high performance network analyzers with 50Ω ports.

The impedance ratio is given as $X:Y$, where X is the secondary port impedance and Y is the primary port impedance. For instance, if the secondary port impedance is 100Ω and the primary port impedance is 50Ω, then the resulting impedance ratio would be 2:1. The primary port is generally designated as the input port, while the secondary port is designated as the output port. Depending on the application or customer requirements, the primary or secondary port designations can be swapped.

Insertion Loss

The insertion loss of an RF transformer is the amount of signal power dissipated or otherwise lost within the device, referenced from the input signal power to the output signal power. All real transformers suffer some insertion loss, and due to the complex nature of RF transformer frequency response, these devices tend to exhibit increased insertion loss at some known upper and lower frequency limits.

The core material for RF transformers has magnetic permeability properties that are a function of temperature. The insertion loss of an RF transformer is sometimes depicted as a plot of insertion loss versus frequency at specific temperatures. The datasheet for a given model usually provides a temperature range where the specific insertion loss is measured.

It is common to see an insertion loss plot of these devices show frequency over a logarithmic scale instead of a linear scale, as transformers are generally broadband

devices covering several frequency octaves. For example, Figure 1 illustrates a transformer's insertion loss performance over frequency at three temperatures.

It is generally desirable for the insertion loss of an RF transformer to be as low as possible within the operating frequency range. The exact insertion loss requirement depends on the circuit. For example, a transformer with high insertion loss in a transmitter signal chain will reduce overall transmitter efficiency. Furthermore, the loss from the signal will dissipate as heat and cause thermally induced performance degradation, or device failure. In a receiver signal chain, an RF transformer with low insertion loss will result in better receiver sensitivity.

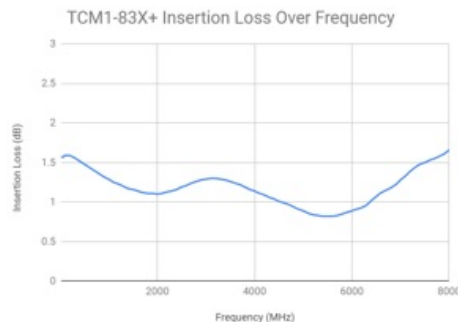


Figure 12: Average Insertion Loss of a Mini-Circuits TCM1-83X+ RF Transformer

Mid-band Loss

The mid-band region of an RF transformer refers to the range of frequencies at which the device exhibits the lowest insertion loss while staying relatively flat throughout the range. The amount of insertion loss in the mid-band region is commonly referenced as mid-band loss, and is typically the lowest insertion loss for the device. For some broadband applications, mid-band loss is of critical interest, whereas in other applications, an RF transformer may be used at operating frequencies outside of the mid-band region.

It is important to note that the mid-band region is generally not in the “middle” of the observable performance of an RF transformer over frequency, which may be easily misunderstood given the common methods of plotting transformer insertion loss performance over a logarithmic frequency scale.

3 dB Bandwidth

The loss of an RF transformer is often described as being a parabolic frequency response. This means that there is a significant increase in insertion loss at lower and higher ends of the frequency range. It is useful to know when the insertion loss of a transformer is less than a relatively standard amount, such as the commonly used 3 dB point. Hence, the 3 dB bandwidth of an RF transformer is the frequency range at which the insertion loss of the device is less than 3 dB greater than the device's lowest insertion loss mid-band loss). The 3 dB bandwidth of an RF transformer is variable over temperature, and temperatures outside of the specified operating temperature range may exhibit degradation of the 3 dB bandwidth metrics.

Return Loss

When an RF transformer's output is connected to a perfectly matched load and a signal is induced at the input, there is invariably a reflected signal. The ratio of the reflected signal power to the input signal power is known as the return loss. This performance metric is useful in determining how strong the reflected signals will be from the input of the transformer, as some devices and circuits before the transformer in the signal chain may be susceptible to undesirable effects caused by those reflections.



Figure 13: Average Input Return Loss of Mini-Circuits TCM1-83X+ RF Transformer

Amplitude Balance (Unbalance)

In the case of differential outputs of an RF transformer, the amplitude balance is the difference in magnitude of one differential output to the other. For many RF circuits, it is desirable to have signal power on balanced lines be as close to equal as possible in order to achieve fully-differential performance and reduce the amount of stray currents present in the signal path.

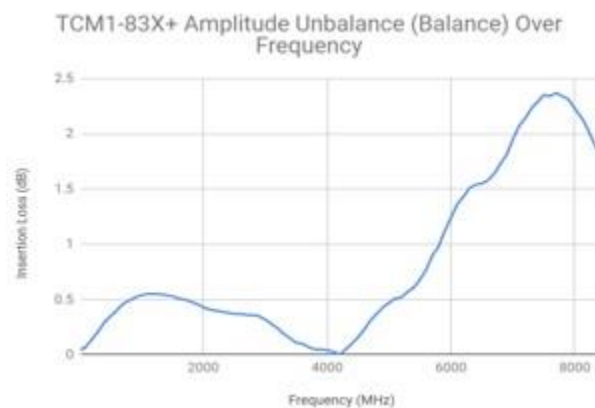


Figure 14: Average Amplitude Unbalance of a Mini-Circuits TCM1-83X+ RF Transformer

Phase Balance (Unbalance)

An RF transformer's phase balance is a measure of how much phase difference there is between the device's two differential outputs, referenced to 180 degrees. The length of the signal path through an RF transformer is a major factor in the phase of its output. Matching the signal path length between the two outputs is therefore critical in achieving good phase balance.

An ideal RF balun transformer, for example, would have no difference between the amplitudes of its outputs, and the output signals would be exactly 180 degrees out of phase. In this case, the CMRR of an ideal balun would be infinite. Considering a real-world device would have some amplitude and phase imbalance. The CMRR is finite and a function of both phase and amplitude imbalance.

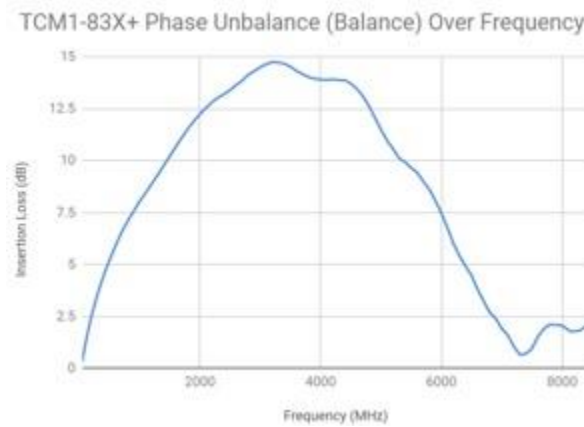


Figure 15: Average Phase Unbalance of a Mini-Circuits TCM1-83X+ RF Transformer

Common-Mode Rejection Ratio (CMRR)

The amount of attenuation common-mode signals incur from input to output when injected at the differential ports of a transformer (typically a balun) is known as the Common-Mode Rejection Ratio (CMRR). In some RF circuits, it is desirable to reduce the amount of common-mode signal from one node to another. In these cases, choosing an RF transformer (i.e. balun) with high CMRR can help to achieve this goal.

Max DC Current

If current beyond a certain threshold passes through an RF transformer, the magnetic field within the core may exceed the saturation tolerances, and the transformer may become saturated. In this state, the device suffers from degraded RF performance. There are methods to enhance the current carrying potential of RF transformers by using winding patterns to create opposing magnetic fields.

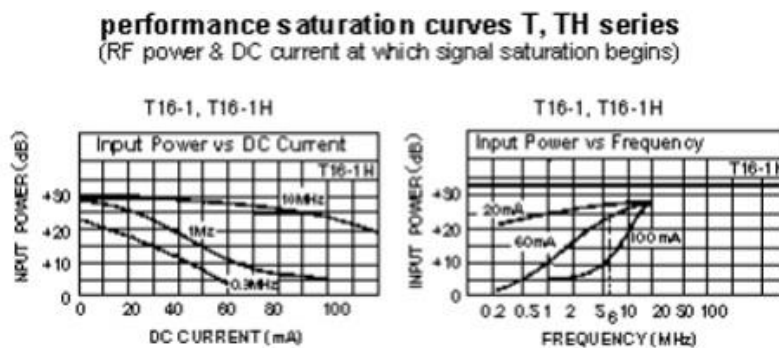


Figure 16: A plot of RF transformer saturation for DC current and RF input power

Max RF Power & Curie Temperature

Operating an RF transformer beyond the specified maximum RF power could lead to saturation of the core, increased insertion loss, and potentially even permanent damage through overheating. The Curie temperature of magnetic cores is the temperature at which the material's magnetic properties degrade. Power and temperature ratings for RF transformers are typically determined in order to stay well below the Curie temperature. As the resistance of the conductive winding of a transformer is also a function of temperature, the maximum RF power threshold before overheating is a function of temperature and should be kept in mind when using RF transformers in extreme environments.

Operating Temperature

The way in which the operating temperature of an RF transformer is specified largely depends on the application. Typically, this metric is specified to avoid operation above or below the acceptable temperature range. As previously mentioned, RF transformers may suffer performance degradation and even permanent damage at some temperatures. This metric is important to understand, considering magnetic core transformers are highly sensitive to performance changes as a function of temperature.

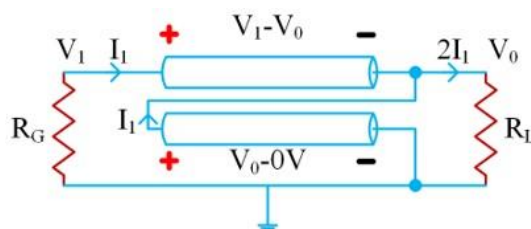
Transformer Max Height

Many technologies of RF transformers are still hand-made or otherwise vary in physical tolerances, such as with core size, epoxy bonding, top hat thickness, etc. Therefore, a transformer's maximum height provides a metric that can be used to ensure adequate clearance within an assembly or enclosure for these devices. As the max height specification is only based on the tallest feature in the case outline, the actual transformer height is generally smaller than the specification.

Conclusion

This concludes Part 3 of the Demystifying of RF Transformers Series on key RF transformer parameters. The last section, (Part 4) dives into methods for selecting RF transformers from a general perspective, and offers several application-specific recommendations.

Part 4: Guide to Selecting RF Transformers



Introduction

So far, this series has provided a survey of RF transformer theory and the technologies behind the various types of RF transformers commonly used in RF system design. The previous sections dove into baluns & ununs and provided a deeper understanding of RF transformer performance parameters. This section concludes the series with considerations to keep in mind when selecting RF transformers for your application. We will also include a description of Mini-Circuits' current RF transformer technologies and methods for selecting a transformer configuration that best meets your specific requirements.

Questions to Ask When Selecting A Transformer

Selecting a component for any RF application requires a complex decision-making process, from modeling and simulation to determining the performance criteria for a signal chain. Since the functions of RF transformers are essential in some applications, the performance and capability of a transformer can have significant impacts on the gain and power budgets for the rest of the signal chain. Selecting the appropriate transformer for a given application is therefore very important for optimal RF design.

For example, it is important to know the DC and power requirements of a given RF circuit, since some RF transformer configurations either isolate, pass, or allow injection of DC current up to a nominal maximum power rating. The selection process includes several other factors as well, and can be broken down into steps with the aid of the RF transformer configuration guide included later in this section.

Step 1: What frequency range is required of the transformer?

Filtering a selection of transformers down to the desired frequency range for your application can narrow down the candidate pool significantly. Most applications have an operating frequency range determined by the 3 dB bandwidth. RF transformer frequency range is typically defined by the 3 dB bandwidth, not the full frequency range (bathtub curve), and it is relatively easy to match the system frequency range with a transformer frequency range. Because RF transformer technology greatly influences operating frequency range, the frequency requirements may predetermine the technology needed. This is especially true for applications beyond several gigahertz where there are fewer core & wire transformers that support these frequencies. This means that transmission line, LTCC, and MMIC transformer designs are more common.

Step 2: What impedance ratio is needed to ensure proper match?

If impedance matching or transformation is required in a circuit, this is likely how a transformer will be used. Characteristic impedances are typically decided by system designers during the modeling and simulation phase of the design process. It is important to remember that the impedance ratio of a transformer directly impacts the

return loss when inserted in a system, and there may be performance limitations that influence ratio requirements.

Step 3: What kind of mounting and connector interface is needed?

Depending on the transformer technology and typical applications for different transformer types, the transformer may be packaged in a connectorized assembly, in a surface mount package, or as a bare die. It is important to consider the type of parasitics, loss, reflections, and other real-world effects inherent to different device housings before deciding on a particular RF transformer package and interface type.

For surface mount applications, there are core & wire, LTCC and MMIC devices available. Some applications may require wire bonding of bare die into compact assemblies.

Step 4: Is a balun configuration needed?

Not all RF transformer configurations can be used as baluns. For instance, Configuration D transformers are autotransformers, and are not suited to balun use. Configurations A, C, G, J, R, and K are commonly used as baluns. (Refer to Table 2 below).

Step 5: Is there a need for DC isolation or DC injection?

Only certain transformer configurations support DC isolation and DC injection. For DC isolation, configurations A, B, C, and E are viable, while for DC injection, configurations A, B, and K can be used. (Refer to Table 2 below).

Step 6: Are there footprint or height constraints?

For some applications, there may be strict constraints on footprint size and device height that limit the selection to more compact technologies such as LTCC, MMIC or surface mount core & wire. Because the size of an RF transformer impacts the frequency range and other performance variables, size constraints may be directly related to electrical performance constraints. For example, the need for an extremely small RF transformer could limit low frequency performance, minimum insertion loss, power handling, DC isolation/injection capability, and impedance ratio.

Step 7: Are there specific RF electrical performance requirements?

Lastly, the remaining RF electrical performance parameters among a manageable selection of RF transformers can be compared and an ideal RF transformer can be identified. These RF parameters include, minimum insertion loss or insertion loss at specific frequencies, amplitude unbalance/balance, phase unbalance/balance, and return loss.

Step 8: Are there other considerations?

There may be additional considerations that are not readily determined during the early simulation and prototyping phase. Some experimentation may be required for which easy sampling options can be crucial in deciding on a specific RF transformer model.

Breakdown of RF Transformer Parameters and Features

Table 1 provides a breakdown of all key RF transformer parameters and features that may need to be considered when selecting an RF transformer for a given application.

Table 1: Breakdown of key RF transformer parameters and features

Electrical Performance Parameters	RF Parameters	■ Frequency range (3 dB bandwidth) 0.005 MHz to 18000 MHz (or DC) ■ Impedance (Port) 50Ω or 75Ω ■ Impedance ratio for proper match 1:1 to 1:36 (or fractional ratios) ■ Amplitude unbalance/balance ■ Phase unbalance/balance ■ Return loss
	RF Transformer Function	■ Balun ■ Balanced to balanced ■ Impedance conversion
	General Electrical Parameters	■ DC isolation ■ DC injection ■ Rated DC current ■ Direct current resistance
Configurations & Technology	Configuration	A, B, C, D, E, E1, F, G, H, J, J1, K, L, M, M1, N, P, P1, Q, R, or S (See Table 2 below)
	Center Tap Options	■ None ■ Primary ■ Secondary ■ Primary & Secondary
	Transformer Technology	■ Core & wire ■ LTCC ■ MMIC ■ Quarter-wave transmission line
Mechanical and Physical Features	Interconnect Interface Options & Packaging	■ Coaxial connector ● Core & wire ● Transmission line ■ Surface mount ● Core & wire ● LTCC ● MMIC ■ Wire bond (Die) ■ Plug-in
	Footprint & Height	
Availability and Order Volume	■ Sampling ■ Availability ■ Volume orders	

Table 2: Guide to Mini-Circuits' RF transformer configurations.

Configurations	Type	Min Freq. (MHz)	Max Freq. (MHz)	Characteristics	Configuration Differences & Additional Details
A, B	DC isolated primary and secondary with center tap	0.01	1400	• Exhibits very high DC isolation. • Center tap enables perfect grounding on both sides and provides better unbalance.	Config A and Config B are very similar, except B has center tap available on the both sides.
C, E, E1	DC isolated primary and secondary	0.01	800	• No center tap. • Unbalance is affected due to virtual ground.	• Config C provides DC isolation. • Config E and E1 are used for balun operation as primary connected to ground. • Config E1 is implemented using LTCC technology and can operate from 12 to 18 GHz.
D, D1	Autotransformer	0.05	2500	• Used for impedance transformation. • Allows for any impedance ratio based on number of turns.	• Config D1 is modified version of config D. • Additional capacitor decouples the signal from ground and allows DC to pass.
F	Tri-filar	0.01	200	• User customizable configuration.	• This configuration consists of 3 lines all coupled to each other and can function differently depending on how the 3 lines are interconnected.
G, K	Transmission line transformer	4.5	9000	• Available as core & wire or LTCC. • At lower frequency, coupling between lines is achieved through the magnetic core. • At higher frequency, the coupling is achieved through capacitive coupling. • The LTCC transmission lines are achieved through coupled transmission lines, and are limited in performance at lower frequencies. • Both configurations allow DC passing	• Config G is a simple transmission line transformer, i.e. a bi-filar transformer. • Config K has an additional feedback winding which allows for DC current to be sourced to the Secondary ports without saturating the core, but requires external capacitors are for DC current to be sourced.

				between primary and secondary windings.	
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Configurations	Type	Min Freq. (MHz)	Max Freq. (MHz)	Characteristics	Configuration Differences & Additional Details
H	Guanella Transformer	10	4500	• 4 winding transmission line transformer. • Typically provides 1:4 impedance ratio. • Commonly used as a balun. • Allows for current to be sourced equally to the outputs.	
J, R	Marchand Balun	390	13500	• Planar Marchand Baluns. • Available as LTCC or MMIC. • Operate at much higher and wider frequency bands compared to transmission line transformers. • Provide DC isolation between primary and secondary windings, and the potential to allow for DC bias.	• Config J is for a standard Marchand Balun and the secondary winding is DC grounded. • Config R has the secondary winding decoupled from DC ground, which allows for DC biasing to be applied to the next stage without requiring a decoupling capacitor.
Q	Impedance matching	DC	2500	• 50 to 75 Ohm impedance matching transmission line transformer.	

Transformer Technology & Guidelines

As discussed in the previous sections of this series, there are four main RF transformer technologies, each with distinct electrical and mechanical properties. The limitations or advantages of each RF transformer technology may make it ideal for some applications while precluding its use in others. The following is a brief description of the various RF transformer technologies in terms of capabilities and application-specific considerations.

Core & Wire

Core & wire transformers are most often used for applications below 6 GHz, although some models can operate to nearly 10 GHz. Some of the reasons for this frequency limitation are grounded in the physics surrounding the ferromagnetic core of the transformer. The coils wrapped around the core create a strong magnetic coupling, which is mainly confined between the core and loops. Losses, as well as the impact of the interwinding capacitances tend to increase for this type of transformer at higher frequencies.

Beyond 1 GHz, capacitive coupling is much greater than magnetic induction in terms of signal transmission. As this effect is a function of size, there are frequency limitations based on the physical size of a core & wire transformer. The size of the wire and core are also major factors in determining the power handling of these transformers. Power handling is also largely limited by the saturation of the ferrite core, which is why these types of transformers are typically limited to less than 1W of power.

Core & wire transformers are typically made of heavy metals and are relatively bulky compared to planar RF transformer technologies. Therefore, applications that require compact size devices may be better served using LTCC or MMIC transformers.

Quarter-Wave Transmission Line Transformers

Quarter-wave transmission line transformers are typically fabricated using microstriplines or coaxial transmission lines with specific impedances. They are called quarter-wave transformers because they are sized to be $\frac{1}{4}$ of the wavelength of the desired operating frequency. As a result, the frequency performance of these transformers is directly related to the physical length of the transmission line and are therefore also band-limited. Quarter-wave transmission line transformers can be made to operate at frequencies over 13 GHz. These transformers are often assembled in coaxial connectorized packages, which are fabricated using the coaxial cable transmission lines that makeup the transformer.

LTCC

Low temperature co-fired ceramic (LTCC) RF transformers are designed using a planar construction method that is extremely repeatable and produces a robust and reliable device. Hence, LTCC transformers are often used in Hi-Rel applications such as

aerospace, space, military communications and radar. These devices come in models that operate to nearly 20 GHz. Like other transformer technologies, the physical construction of these devices impacts the frequency performance limiting low frequency performance to several hundred MHz. However, high frequency LTCC RF transformers are extremely compact and ideal for low-profile surface mount applications.

MMIC

Monolithic Microwave Integrated Circuit (MMIC) technology can be used to fabricate extremely small RF transformers with good high-frequency performance beyond 13 GHz. Due to their small size, these types of transformers are typically limited to low frequency performance down to several GHz. These devices are either delivered in surface mount compatible packages or as bare die for wire bonded assemblies.

Conclusion

RF transformers are a key component of many RF systems, and will likely continue to be increasingly useful as RF and digital systems are more tightly integrated and the bandwidth requirements for communications systems continues to grow. Therefore, it is highly valuable to have a clear approach to selecting RF transformers for an application, which includes an understanding of RF transformer theory, performance parameters, technology, and applications.

RF Transformer Fundamentals

1 Introduction

The purpose of this article is to describe the fundamentals of RF and microwave transformers and to provide guidelines to users in selecting proper transformer to suit their applications. It is limited to core-and-wire and LTCC transformers.

2 What is a Transformer

A transformer is a passive device that “transforms” or converts a given impedance, voltage or current to another desired value. In addition, it can also provide DC isolation, common mode rejection, and conversion of balanced impedance to unbalanced or vice versa, as explained later. Transformers come in a variety of types; our focus is on transformers used in RF and Microwave signal applications. Essentially, an RF transformer consists of two or more windings linked by a mutual magnetic field. When one winding, the primary has an AC voltage applied to it, a varying flux is developed; the amplitude of the flux is dependent on the applied current and number of turns in the winding. Mutual flux linked to the secondary winding induces a voltage whose amplitude depends on the number of turns in the secondary winding. By designer’s choice of the number of turns in the primary and secondary windings, a desired step-up or step-down voltage/current/impedance ratio can be realized.

3 Why are Transformers Needed

Transformers are used for:

- Impedance matching to achieve maximum power transfer between two devices. Voltage/current step-up or step-down.
- DC isolation between circuits while affording efficient AC transmission.
- Interfacing between balanced and unbalanced circuits; example: push-pull amplifiers, ICs with balanced input such as A to D converters.
- Common mode rejection in balanced architectures.

4 How are They Made

An RF transformer usually contains two or more insulated copper wires twisted together and wound around or inside a core, magnetic or non-magnetic. Depending on design and performance requirements, the core can be binocular as in Figure 1, toroid (doughnut shaped) as in Figure 2 etc. Wires are welded or soldered to the metal termination pads or pins on the base. The core and wire ensemble is housed in a plastic, ceramic or metal case.

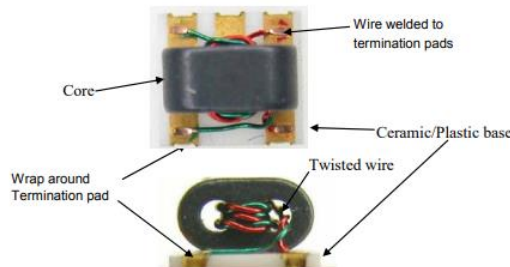


Figure 1 Open Case Transformer (Binocular Core)

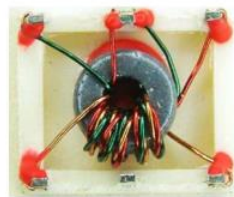


Figure 2 Toroidal Core

Ideal Transformer

At low frequencies, an alternating current applied to one winding (primary) creates a timevarying magnetic flux, which induces a voltage in another (secondary). At high frequencies, the inter-winding capacitance and magnet wire inductance form a transmission line which helps propagate the electromagnetic wave from primary to secondary. The combination of magnetic coupling and transmission line propagation helps the transformer to achieve outstanding operating bandwidths (1:10000 or more). Figure 3 shows ideal circuit of a simplified two-winding transformer.

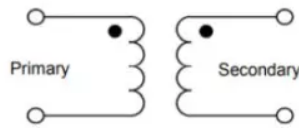


Figure 3: Transformer equivalent circuit.

6 Dot Convention of Ideal Transformer

If at the dotted end of the primary winding the voltage is positive with respect to the undotted end, then the voltage at the dotted end of the secondary is also positive with respect to the un-dotted end as shown in Figure 4. Also, if primary current flows into dotted end of the primary winding, current flows out of the dotted end of secondary winding (at low frequencies, neglecting the small insertion phase, current I_1 entering the dot at primary is in phase with current I_2 exiting the dot).

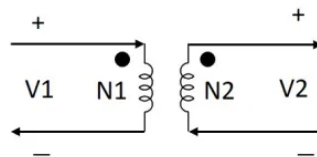


Figure 4: Transformers showing dot convention with respect to voltage and current direction.

In Figure 4, N_1 and N_2 are number of turns and V_1 and V_2 are voltages at the primary and secondary respectively.

7 Transformer Equations

$$n = N_2/N_1$$

$$V_2 = n V_1$$

$$I_2 = I_1/n$$

$$Z_2 = n^2 Z_1$$

Faraday's law of induction states that, the voltage V induced in a coil is equal to the change of magnetic flux linkages $N\Phi$ with respect to time. Based on the above, transformer equations shown above are derived.

It states that the output voltage (V_2) is equal to turns ratio (n) times the input voltage (V_1). It also states that, output current (I_2) is input current (I_1) divided by the turns ratio and output impedance (Z_2) is input impedance (Z_1) multiplied by the square of the turns ratio.

For example; if $n=2$ and $Z_1=50\Omega$:

$$V_2=2V_1$$

$$I_2=I_1/2 \text{ and}$$

$$Z_2=4Z_1=200\Omega.$$

8 What is a Balun?

Before defining what a balun is, we need to define balanced and unbalanced impedances. A balanced two-terminal impedance has neither of its terminals connected to ground, whereas an unbalanced impedance has one of its terminals connected to ground; see Figure 5.

By definition, a balun is a device which transforms balanced impedance to unbalanced and vice versa.

In addition, Baluns can provide impedance transformation, thus the name Balun Transformer. Most transformers can be used as baluns, an example of the same is shown in Figure 6.

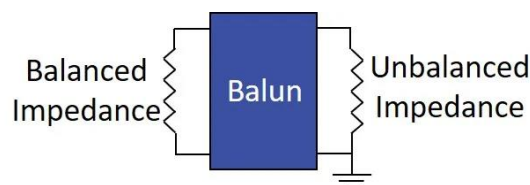


Figure 5: Balun.

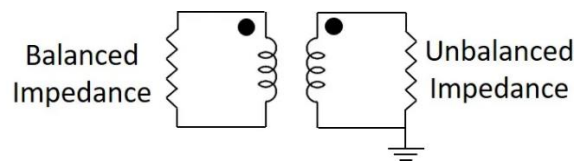


Figure 6: Transformer can function as a Balun.

9 Applications of Transformers/Baluns-Example

9.1 Common Mode Rejection

One of the most common applications of a balun is for common-mode signal rejection. To illustrate common mode rejection properties of a balun, let us use as an example a dual amplifier in cascade with a 1:1 transformer (balun). It is assumed in this example that the S-parameters of the dual amplifiers are identical and the balun is ideal.

When two signals V_{DI} of equal magnitude but opposite polarity (differential signals), are applied to the inputs of a dual amplifier, they are amplified and appear at the output as two signals of equal magnitude (V_{DO}) but opposite polarity as shown in Figure 7. These signals are combined in T1 (1:1 Balun) and result in a signal of magnitude $2V_{DO}$.

When two signals V_{CI} of equal magnitude and same polarity (common mode signals) are applied to the inputs of a dual amplifier, they are amplified and appear at the output as two signals of equal magnitude (V_{CO}) and of same polarity as shown in Figure 8.

These signals are combined in T1 (balun), where they cancel and result in a signal of magnitude 0V at output of T1.

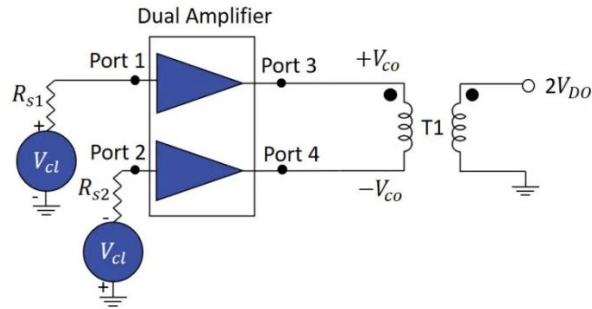


Figure 7: Dual amplifier excited by different signals.

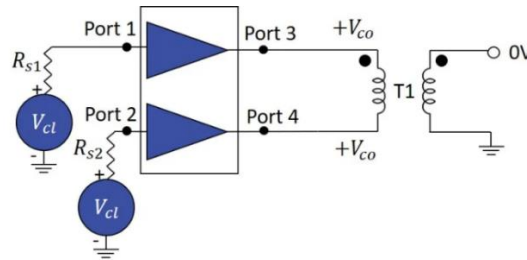


Figure 8: Dual amplifier excited by common mode signals.

In reality, both unwanted common mode and wanted differential signals are applied to the input of dual amplifier as shown in Figure 9. A balun does a wonderful job of rejecting the common mode signal and combining the differential mode signals.

To illustrate the benefits of common mode rejection in a balun, let us take two examples; a PC board having single ended devices (such as amplifiers, mixers etc.) interconnected with unshielded transmission lines such as microstrip and a PC board having balanced devices interconnected with unshielded transmission lines.

In case (i) any in-band interfering signal, such as radiation from adjacent circuits, is added to the desired signal and there is no way of separating the wanted from the unwanted. This results in degradation of system performance such as signal-to-noise ratio.

In case (ii), the interfering signal is of equal amplitude (due to close proximity) on both lines feeding a balanced device. When the output of such balanced device is converted into single ended by using a balun, the interfering signal, which is common mode in nature, is rejected.

In an ideal balun, signals appearing at the output of balanced ports are of equal amplitude and differ in phase by 180° . In reality, even in a well designed balun/transformer, there is a small amplitude and phase unbalance. Amplitude unbalance is difference in amplitude (in dB) and phase unbalance is deviation from 180° phase, in degrees. A well-designed transformer might have 0.1 dB amplitude and 1° phase unbalance in the mid-band. Unbalance results in common mode rejection being finite instead of nearly infinite.

9.2 Push-Pull Amplifiers

Benefits:

Even-order harmonic suppression, which is a big deal in wideband Cable TV application ~3 dB higher Pout & IP3 than a single device.

Wideband communication systems have signals occupying multi-octave frequency range. For example, CATV signals occupy 50-1000 MHz range, which is more than four octaves. Such signals when amplified in conventional amplifiers can be distorted due to the second order products generated inside the amplifier.

For example, second harmonic of 50 MHz signal is 100 MHz, so also second harmonic of 400 MHz which is 800 MHz and both are within the band.

An ideal push-pull amplifier can cancel the internally generated products and preserve the signal quality. Figure 10 shows a simplified schematic of such an amplifier. It consists of two baluns and two identical amplifiers. When a signal is applied to the input of the first balun (Balun #1), the output signal from the same balun consists of two signals of equal amplitude and out of phase. These signals are amplified combined in output balun (Balun #2).

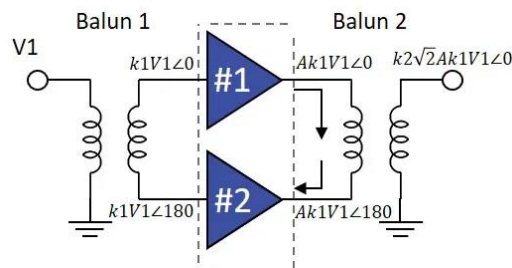


Figure 10: Simplified schematic of a push-pull amplifier.

The gain of a push-pull amplifier is same as that of an individual amplifier, whereas the output power is twice that of an individual amplifier. Push-pull connection is frequently used for combining power of individual amplifiers.

An additional benefit, push-pull amplifiers cancel even-order harmonics, as even-order harmonics are in-phase. An example is shown in Figure 11 for second harmonic. Same is true for other even order products falling within the operating bandwidth of the transformer.

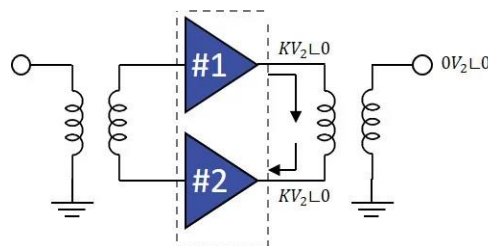


Figure 11: Even-order harmonics cancelled in push-pull amplifier.

As an example, Mini-Circuits HELA-10+ consists of a pair of amplifiers. As they are on the same chip, their gain and phase are very well matched. If a balanced signal is applied to the input of the HELA-10+ then the output is also balanced. By using a set of baluns (or transformers) at the input and output a single ended input is first converted into a balanced signal in T1, amplified in HELA-10, and combined in the transformer T2 to produce a single-ended output. IP2 of such an amplifier is in excess of 87 dBm.

Figure 12 shows a push-pull amplifier using transistors. Base biasing is applied through center tap of T1 and collectors through T2. Configurations A,B and F can be used for this application. By using blocking caps, at input, configuration H can be used.

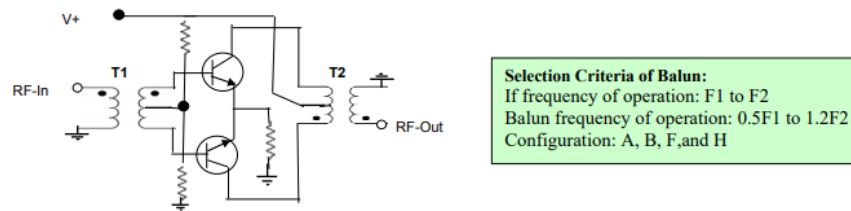


Figure 12 Push-Pull amplifiers using Transistors & Baluns

9.3 Power Splitter 180°

Output signals of an ideal transformer are of equal magnitude and of opposite phase as shown in Figure 13 and hence can be used as a 180° splitter.

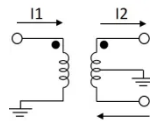


Figure 13: 180° splitter.

9.4 Double Balanced Mixer

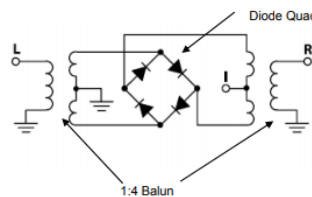
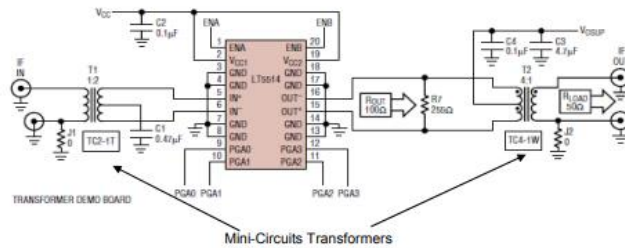


Figure 14 Double balanced mixer

In its simplest form, it consists of a pair of 1:4 baluns/transformers and a diode quad. Center tap of the LO transformer is grounded and center tap of the RF balun (right) is used for extracting IF (Figure 14).

9.5 Converting Single Ended to Balanced

Many ICs available in the market have balanced input/output terminals. When such ICs have to be interfaced with unbalanced circuits, transformers/baluns are used. Example of the same is shown in Figure 15.



10 Transformer Configurations

Transformer configurations can be broadly classified as: Conventional; core-and-wire based (Configurations A, B, C, D, F) Transmission line; core-and-wire and LTCC (Configuration G,H,K) Marchand; LTCC (Configuration J)

See Table 1 for the schematics, frequency of operation, impedance ratio, important electrical parameters and applications

Conventional transformers made of core-and-wire optionally have center tap on primary or secondary or on both sides and are limited to an upper frequency of 2 GHz. Most configurations have DC isolation from primary to secondary.

Transmission line type transformers using core-and-wire operate to 3 GHz and using LTCC to 5 GHz or higher and do not have DC isolation from primary to secondary. External blocking capacitors are needed to realize isolation.

Marchand (named after the inventor) transformers operate to 6 GHz and higher and are realized in LTCC form and have DC isolation from primary to secondary.

Selection of a transformer for an application can often be confusing and sometimes results in the wrong choice. The following guidelines attempt to clarify the options and state the benefits of various configurations.

For impedance matching (unbalanced to unbalanced) applications; choose auto transformer (Configuration –D), in general it provides lowest insertion loss. For balun applications, choose a balun with center tap on balanced side as it provides excellent amplitude and phase balance (Configurations A, B, H, J).

For balanced-to-balanced transformation, choose a transformer with center tap on both primary and secondary (Configuration B, L) as it provides excellent amplitude and phase balance on both sides.

For DC isolation between primary and secondary, do not choose transmission line configurations (G, H, K,). If needed; add DC blocking caps to isolate primary and secondary.

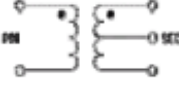
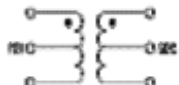
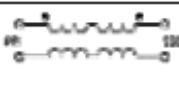
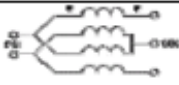
Configuration	Schematic	Description	Frequency (MHz) Typical maximum range	Impedance ratio Typical maximum ratio	Unbalance	DC Isolation	Power handling Typical use	Applications		
								Impedance Conversion	Balun	Balanced to Balanced
A		DC isolated primary and secondary, center-tap secondary	0.01 to 1400	1 to 16	Excellent	Yes	Up to 1W	YES	YES	YES
B		DC isolated primary and secondary, center-tap primary and secondary	0.004 to 500	1 to 25	Excellent	Yes	Up to 0.25 W	YES	YES	YES
C		DC isolated primary and secondary	0.01 to 1200	1 to 36	Average	Yes	Up to 0.25 W	YES	YES	YES
D		Auto transformer	0.05 to 2200	0.1 to 14	N/A	No	Up to 0.25 W	YES	--	--
F		DC isolated, three open windings, Tri-filar transformer	0.01 to 200	1 to 2	Good	No	Up to 0.25 W	YES	YES	YES
G		Transmission line transformer	0.5 to 3000	1 to 4	Good	No	Up to 2 W	YES	YES	YES
H		Transmission line transformer-four windings	10 to 4500	2 & 4	Good	No	Up to 5 W	YES	YES	YES
J		Marchand Balun	600 to 6200	1 to 4	Excellent	Yes	3 W	YES	YES	--
K		Transmission line transformer: Tri-Filar	5 to 3000	1	Excellent	No	Up to 0.5W	--	YES	YES
L		Balanced to balanced transformer	10 to 2200	1.5 to 2	Good	No	Up to 0.25W	YES	--	YES

Table I Summary of Transformer Configurations

11 Characteristics of Transformers

11.1 Insertion Loss

Figure 16 shows the insertion loss of a core-and-wire transformer. The low-end loss is heavily influenced by the primary inductance while the high-end loss is attributed to the losses in inter-winding capacitance, and series inductance.

The permeability of a magnetic core is influenced by temperature. As the temperature decreases, permeability decreases causing an increase in the insertion loss at low frequency.

Figure 17 shows the insertion loss of an LTCC transformer. Note the insertion loss is low over the entire band as the losses in ceramic are minimal and variation with temperature is also minimal.

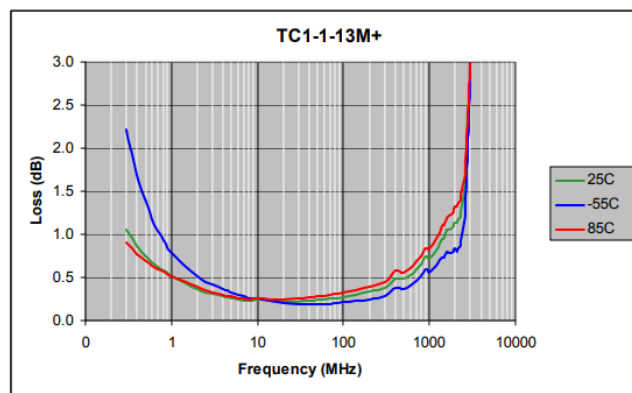


Figure 16 Insertion Loss vs. frequency of core-and-wire transformer

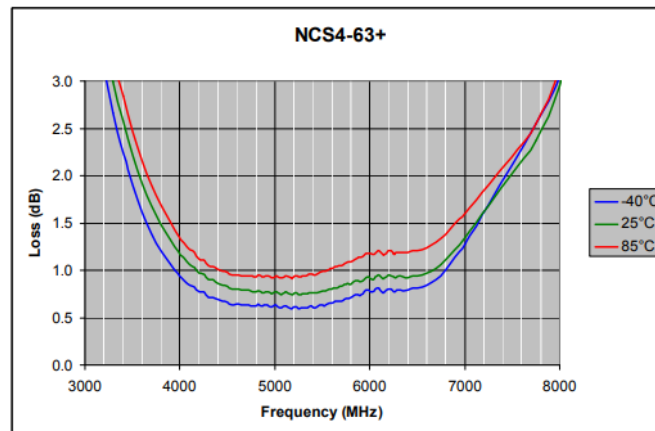


Figure 17 Insertion Loss vs. frequency of an LTCC transformer

11.2 Unbalance: Amplitude and Phase

An incident voltage (V_1) is transformed into two voltages V_2 and V_3 (see Figure 18). In an ideal transformer, the amplitude of V_2 is equal to that of V_3 and the phase difference is 180° . In practical transformers there is small amplitude difference and the phase difference deviates from 180° (see Figure 19). Amplitude unbalance is defined as:

Amplitude unbalance in (dB) = $20 \log_{10} (|V_2|/|V_3|)$.

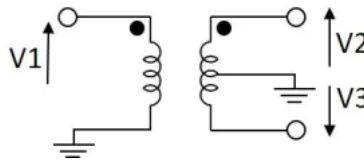


Figure 18: Unbalance in transformer.

Phase unbalance (in degrees) = θ (in degrees).

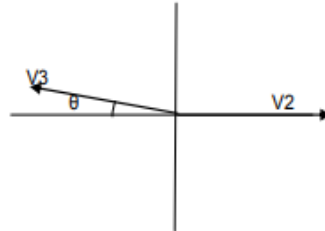


Figure 19 Unbalance-Polar Representation

12 Test Characterization of Transformers

12.1 Insertion Loss

Prior to the availability of modern network analyzers, baluns and transformers having impedance ratio other than 1:1 were connected back to back and the combined insertion loss of two units was measured. Insertion loss of a single device was calculated by dividing the measured loss by 2. This overcame the need to match impedance of devices having output impedance other than 50Ω.

In recent years, baluns have been characterized as 3-port networks, like a two-way 180° splitter. As the impedance at the secondary ports is generally not 50Ω, impedance transformation is essential to do an accurate measurement. One method is to use resistive matching pads at the secondary for that purpose. In this method insertion losses from primary dot to secondary dot and primary dot to secondary are measured. The average of these two losses after subtracting the loss of the matching pad and 3 dB for loss due to theoretical split, is specified as insertion loss.

New network analyzers such as Agilent's PNA series provide impedance transformation and port extension capabilities so that there is no need to add resistive matching pads. A PNA analyzer enables 3-port measurement for any user-defined input and output impedances.

12.2 Unbalance: Amplitude and Phase

The set up used for charactering a transformer as a 3-port network provides two insertion losses (primary dot to secondary dot and primary dot to secondary) in vector form. The difference of these two magnitudes in dB is called amplitude unbalance. The phase angle deviation from 180° is phase unbalance.

12.3 Input Return Loss

When the secondary is terminated in its ideal impedance, the return loss measured at the primary is the input return loss. It is a measure of the effectiveness of the balun in transforming impedance.

12.4 S-Parameters

By using a multi port network analyzer, S-parameters can be measured. The resulting “.snp” file is in Touchstone format and can be used in simulators such as Agilent ADS. When an application needs impedance other than the one specified in the data sheet, “.snp” can be used in simulation software such as Agilent’s ADS (or equivalent) to analyze its performance.

13 Summary

This article is to describe the fundamentals of RF and microwave transformers, most common applications, guidelines to users in selecting proper transformer to suit their applications and measurement methods.

RF Transformers

RF transformers are widely used in low-power electronic circuits for impedance matching to achieve maximum power transfer, for voltage step-up or step-down, and for isolating DC from two circuits while maintaining ac continuity. They are also used for common mode rejection and as baluns.

Essentially, an RF transformer consists of two windings linked by a mutual magnetic field. When one winding, the primary has an AC voltage applied to it, a varying flux is developed; the amplitude of the flux is dependent on the applied voltage and number of turns in the winding. Mutual flux linked to the secondary winding induces a voltage whose amplitude depends on the number of turns in the secondary winding. By designing the number of turns in the primary and secondary windings, any desired step-up or step-down voltage ratio can be realized. Mutual coupling is accomplished simply with an air core but considerably more effective flux linkage is obtained with the use of a core of iron or ferromagnetic material with higher permeability than air.

The relationship between voltage, current, and impedance between the primary and secondary windings of the transformer may be calculated using the following relationships. With reference to Figure 1:

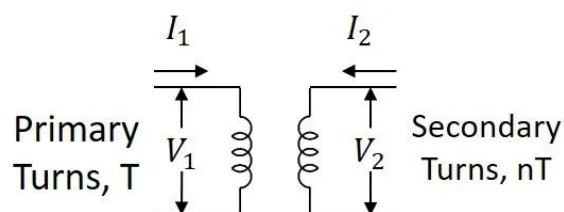


Figure 1

$$V_2 = nV_1$$

$$I_2 = I_1\sqrt{n}$$

$$Z_2 = \frac{V_2}{I_2} = \frac{nV_1}{I_1\sqrt{n}} = n^2 \frac{V_1}{I_1} = n^2 Z_1$$

$$\text{Thus, } Z_2 = n^2 Z_1$$

As an example, if Z equals 50Ω and the turns ratio equals 2, the secondary impedance equals 200Ω . In this case, the secondary voltage is twice the primary voltage and the secondary current is one-half the primary current.

The basic phase relationship between the RF signals at the transformer input and output ports may be in – phase, 0° , or out-of-phase, 180° . Conventionally, the ports that are in-phase 1, and 3, are marked by dot notation as shown in Figure 2. Ports 1, 4 and 2, 3 are out-of-phase, 180° .

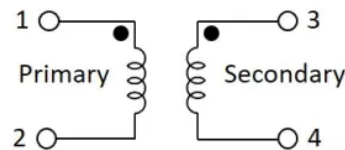


Figure 2

Mini-Circuits' transformers are physically assembled by winding a pair of twisted wires around a ferrite toroidal core. The ends of the primary and secondary wires which leave the same side of the toroid are in the in-phase ports (Figure 3).

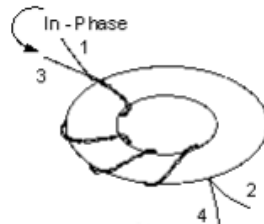


Figure 3

For transformers that have a secondary winding with a center-tap, the schematic representation and dot locations are shown in Figure 4.

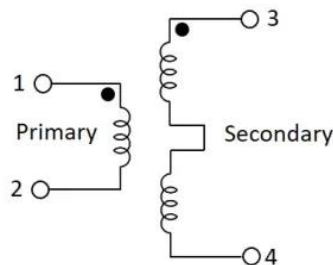


Figure 4

In this case ports 1 and 3 are in-phase, 0° , and ports 1 and 6 are out-of-phase, 180° . These transformers may be operated as low as 12.5Ω at the primary with essentially the same impedance matching ratio and only a slight change in frequency response. For convenience, all Mini-Circuits transformers are specified as a step-up.

For each RF transformer model, the minimum and maximum frequency is given for the insertion loss at the 3 dB, 2 dB and 1 dB points, as shown in Figure 5 and listed in the data chart. For example, the T1-1 insertion loss is 1 dB from 2 to 50 MHz and 3 dB from 0.15 to 400 MHz.

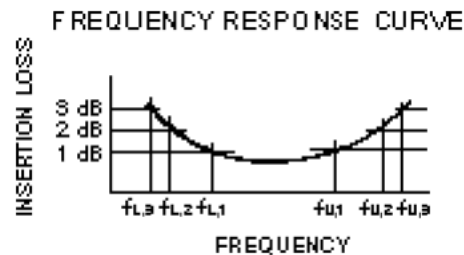


Figure 5

Coaxial connector models are available from 5 KHz to 500 MHz and are offered with 50Ω and 75Ω impedances; 75Ω connectors are used at 75Ω ports. The FT1.5-1, with unbalanced input and output is especially useful for 50Ω to 75Ω matching applications. The FTB series with unbalanced output and balanced input as shown in Figure 6 (connector ground insulated from the case) helps eliminate ground loop problems, especially when long cable runs are involved.

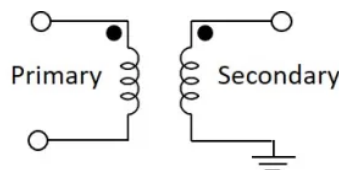


Figure 6

In some applications there is a need to pass a relatively high DC current through the primary winding. In this case, the transformer core may saturate resulting in reduced transformer bandwidth and power handling capability. Mini-Circuits TH series of transformers are designed to handle up to 100 mA in the primary winding without appreciable saturation and change in RF characteristics.

Transformer core saturation is influenced by (1) DC current through the winding, (2) RF input power, and (3) frequency of operation. These three variables interact to affect the point at which saturation occurs. See Figures 7 and 8 in which conventional transformer saturation is compared to the TH series.

Mini-Circuits has developed many special transformer impedance ratios and configurations where high DC current is passed through one winding of the transformer. Many of these designs have been for open package surface-mount requirements. Consult our Applications Department for your particular needs.

performance saturation curves T, TH series
(RF power & DC current at which signal saturation begins)

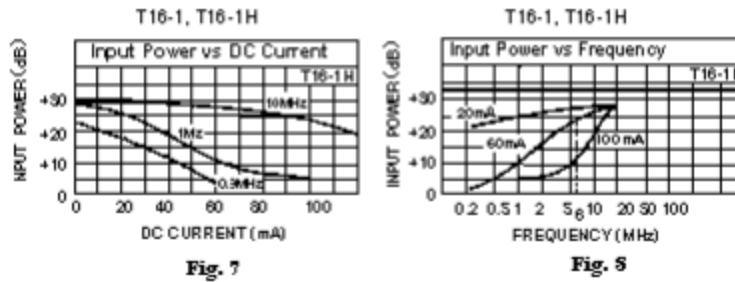


Figure 7

Frequently Asked Questions About RF Transformers

Q: Explain the difference between DC-isolated and non-isolated transformers.

A. A DC-isolated transformer is one that does not allow a DC current to pass between the primary and secondary windings.

Q: Mini-Circuits transformers are tested with 50Ω systems. How do they perform at other impedance?

A. Mini-Circuits' transformers can be used over a wide range of impedance ranges with an impedance as low as 12.5Ω with a only small change in the bandwidth

Q: Are Mini-Circuits' transformers step-up or step-down?

A. All Mini-Circuits transformers are specified as step-up transformers. However, they are tested both ways and may be used as a step-up or a step-down.

Q: Can I just use one side of a center-tapped transformer?

A. Yes. You may use one side of the transformer but you should remember you will obtain only one fourth of the impedance ratio.

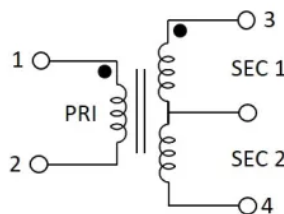


Figure 1

Q: Can Mini-Circuits supply MIL-tested transformers?

A. Yes, Mini-Circuits' hermetically-sealed TMO transformers meet military needs. Please submit your environmental requirements to Mini-Circuits for review.

Q: What are the effects of temperature extremes on Mini-Circuits transformers?

A. The permeability of the core is influenced by temperature. As the temperature decreases, there is a change in the permeability causing an increase in the insertion loss at low frequency.

As temperature increases, the permeability increases thereby slightly decreasing insertion loss at low frequency. This is true, however, as long as the temperature does not increase above the Curie temperature of the core. Mini-Circuits' designs use cores that have a Curie temperature much higher than the highest specified operating temperature.

Q: Explain the reasons for low-end and high-end losses of a transformer.

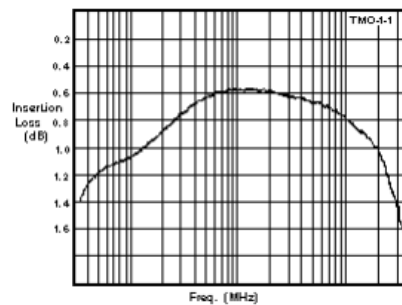


Figure 2

The low-end loss is heavily influenced by the primary inductance while the high-end loss is attributed to the inter-winding capacitance and series inductance.

Q: How do I measure the insertion loss of a transformer?

A. The insertion loss is measured on two transformers connected back-to-back (impedance matched) and dividing the resulting insertion loss by two.

Q: Can I build a power splitter with Mini-Circuits' transformers?

A. You can use the Mini-Circuits' T2-1T, to create a 50Ω, 180° power splitter.

The isolation between output ports and the output return loss of each port will not be as good as a MiniCircuits' standard power splitter.

Q: What are the breakdown voltage ratings of Mini-Circuits' transformers?

A. Mini-Circuits does not typically specify a break down voltage. However, many of our transformers are able to handle up to 1000 VRMS. Please contact the factory about the transformer of your choice.

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