RF and Microwave Transformer Fundamentals

by Mini-Circuits

Introduction

The purpose of this application note 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.

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.

Figure 1: **Open Case Transformer (Binocular Core)**

Figure 2: **Toroidal Core**

Figure 3: **Transformer Equivalent Circuit**
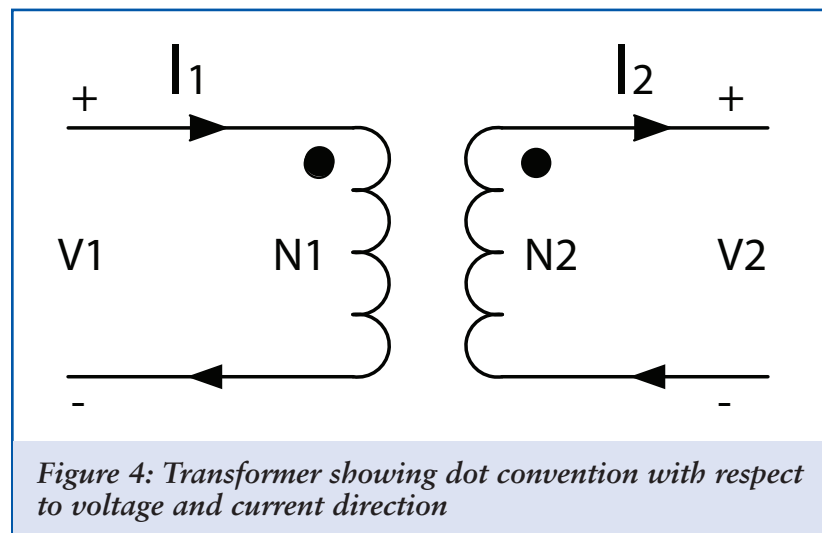
Figure 4: **Transformer showing dot convention with respect to voltage and current direction**

Why are Transformers Needed?

Transformers are used for[1]:

- 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.
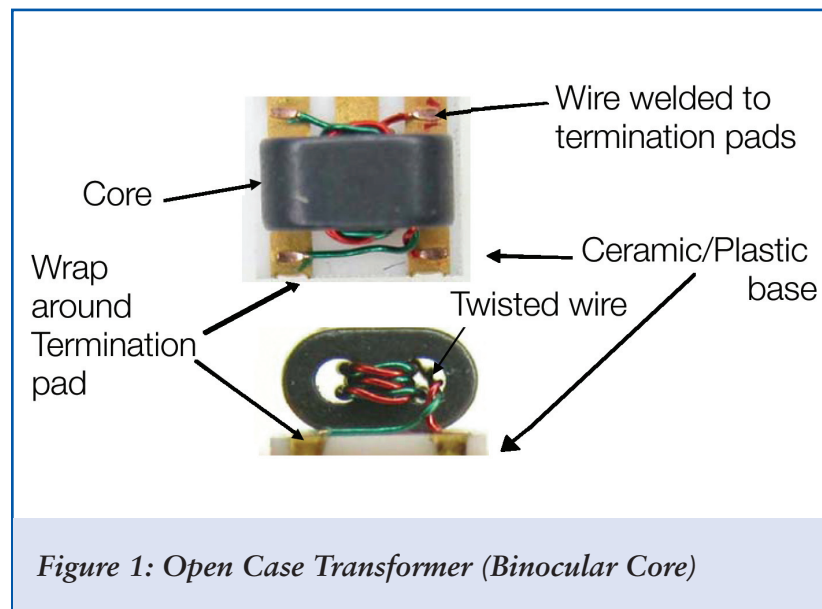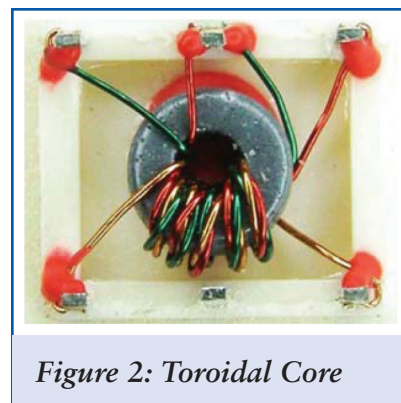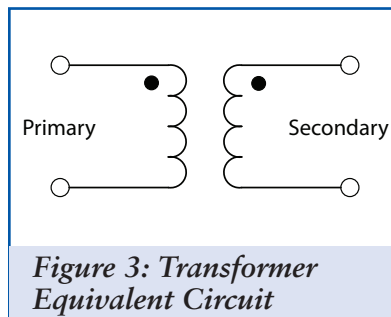- Interfacing between balanced and unbalanced circuits; example: push-pull amplifiers, ICs with balanced input such as A to D converters.
- Common mode rejection in balanced architectures

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.

Ideal transformer

At low frequencies, an alternating current applied to one winding (primary) creates a time-varying 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.

Dot Convention of Ideal Transformer

If at the dotted end of the primary winding the voltage is positive with respect to the un-dotted 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 I1 entering the dot at primary is in phase with current I2 exiting the dot).

In **Figure 4**, N1 and N2 are number of turns and V1 and V2 are voltages at the primary and secondary respectively.

Transformer Equations

$$n = N2/N1$$
$$V_2 = n\ V_1$$
$$I_2 = I_1\ /\ n$$
$$Z_2 = n^2\ Z_1$$

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[2].

It states that the output volt-

age (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 Z1=50 ohms:
$V_2=2V_1$
$I_2=I_1/2$ and
$Z_2=4Z_1$ = 200 ohms

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 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**.

Applications of Transformers/Baluns-Examples

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 $2V_{DO}$.

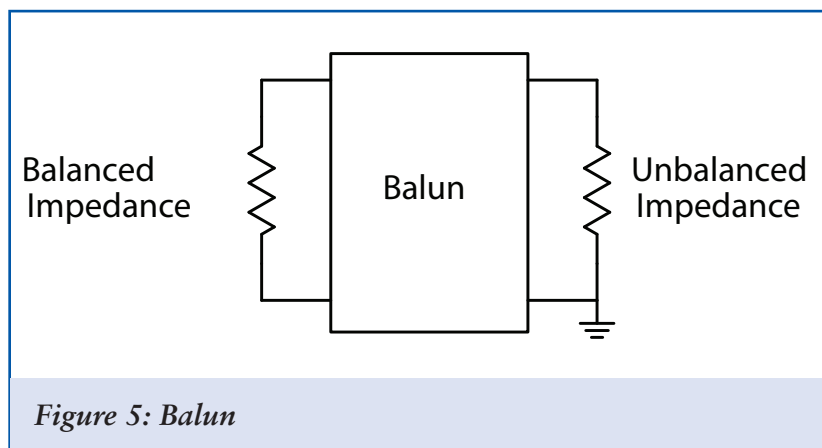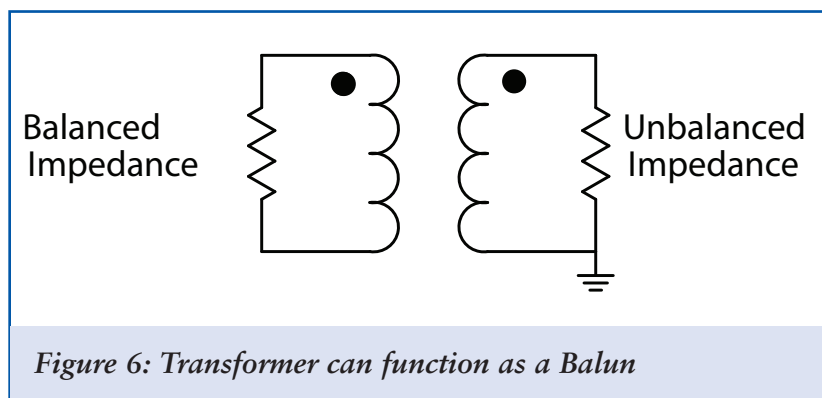When two signals V_{CI} of equal magnitude and same

Figure 5: Balun

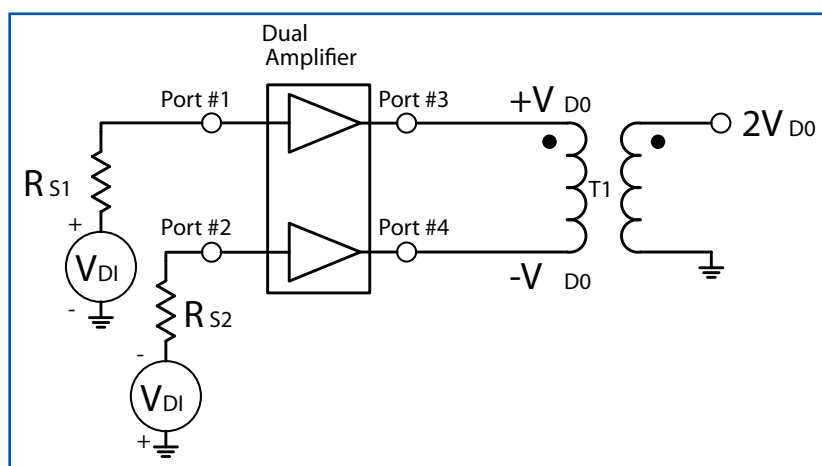*Figure 6: Transformer can function as a Balun*

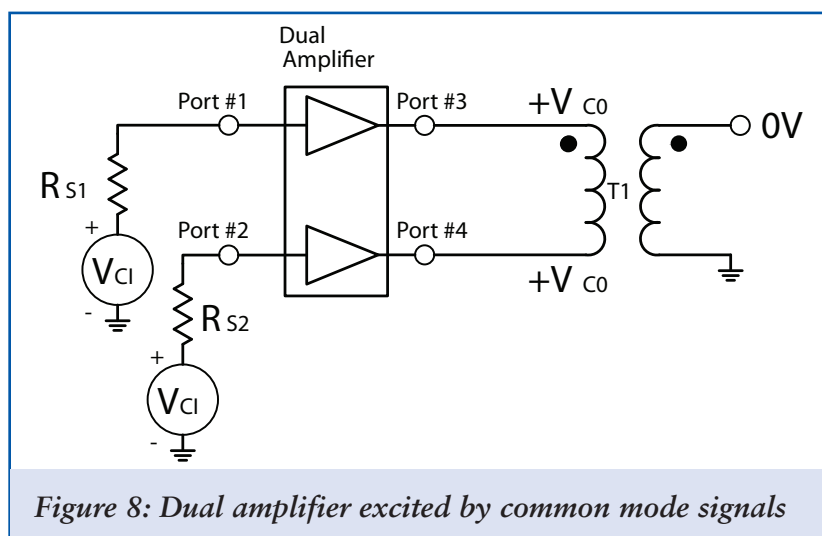*Figure 7: Dual amplifier excited by differential Signals*

Figure 8: Dual amplifier excited by common mode signals

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.

In real life both unwanted common mode and wanted differential signals are applied to the input of dual amplifier as shown in **Figure 9**. Balun does

a wonderful job in 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:
  i. a PC board having single ended devices (such as amplifiers, mixers etc.) interconnected with unshielded transmission lines such as microstrip and
  ii. 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.

Push-Pull amplifiers[3]

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

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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).

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.

As an example, Mini-Circuits HELA-10+ consists of a pair of amplifiers4. 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
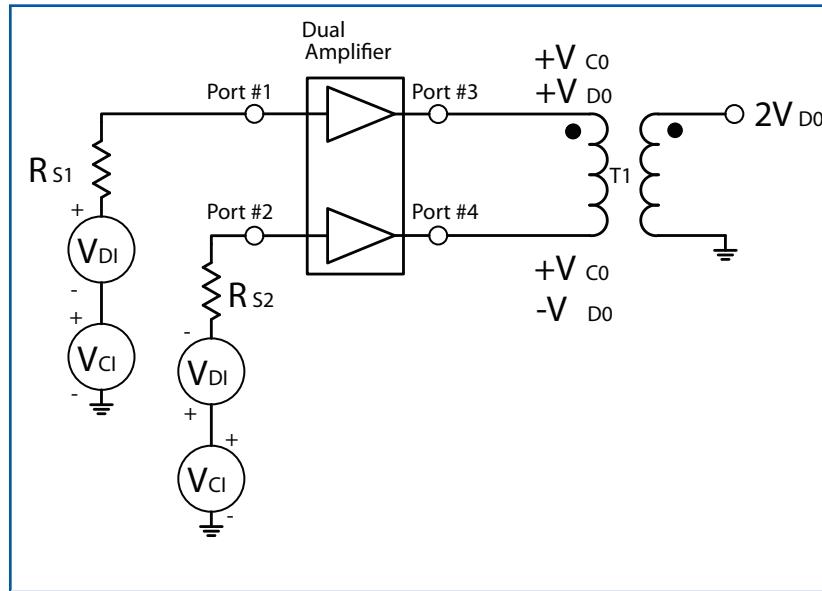

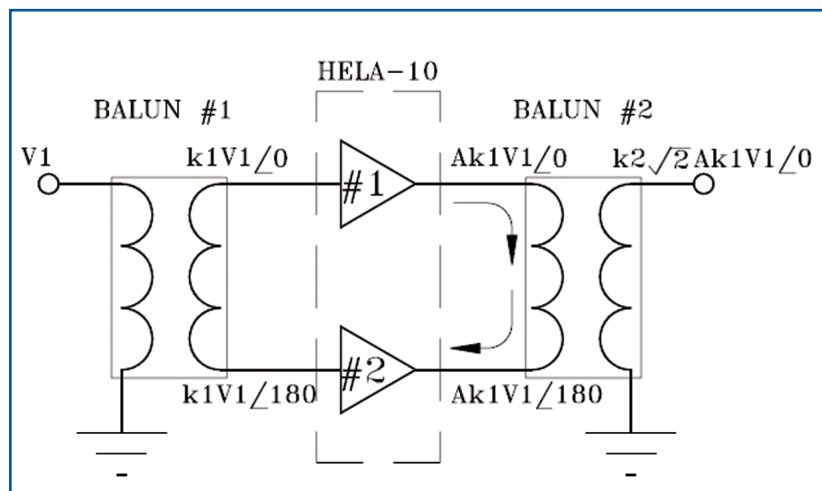*Figure 9: Dual amplifier excited by common mode and differential signals*

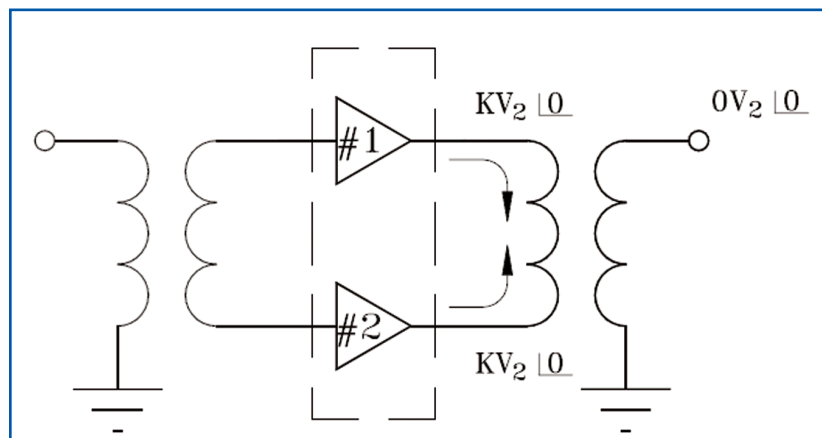*Figure 10: Simplified Schematic of Push-Pull Amplifier*

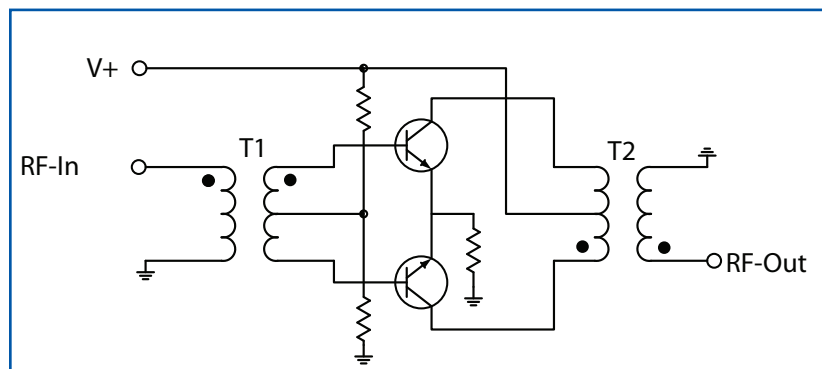*Figure 11: Even-order harmonics cancelled in push-pull amplifier*

Figure 12: Push-Pull amplifiers using Transistors & Baluns

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.

Power Splitter 180º
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.

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 (See **Figure 14**).

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**[5].

Transformer Configurations[6]
Transformer configurations can be broadly classified as:
1. Conventional; core-and-wire based(Configurations A,B,C,D,F)
2. Transmission line; core-and-wire and LTCC (Configuration G,H,K)
3. 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
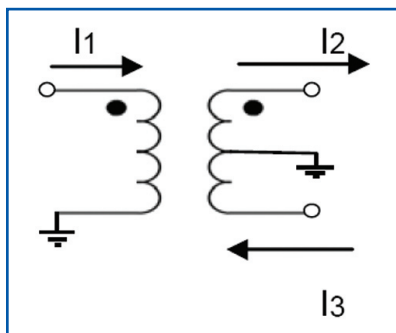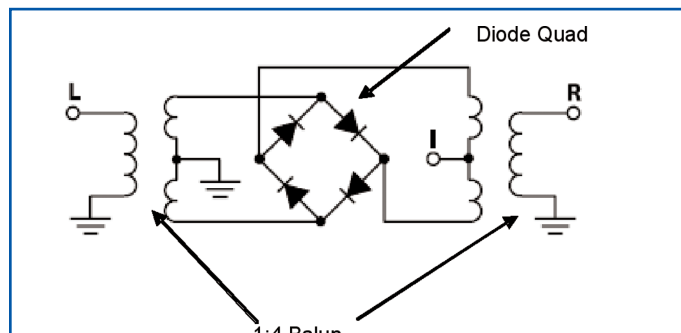
Figure 13: 180° Splitter

Figure 14: Double balanced mixer
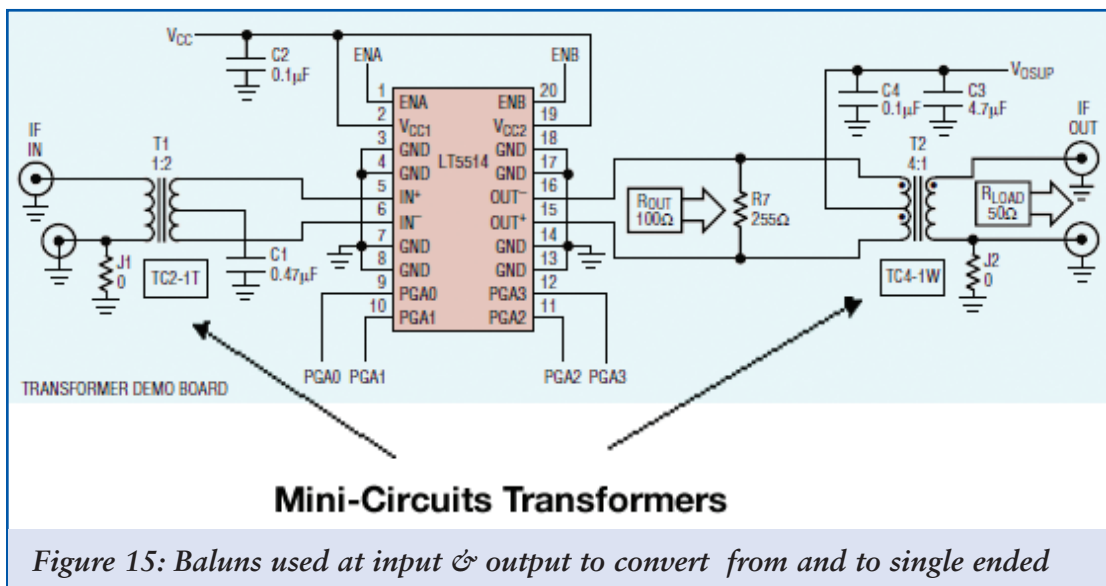

Mini-Circuits Transformers

Figure 15: Baluns used at input & output to convert from and to single ended

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.

i. For impedance matching (unbalanced to unbalanced) applications; choose auto transformer (Configuration –D), in general it provides lowest insertion loss.

ii. 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).

iii. 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.

iv. 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.

Characteristics of Transformers
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.

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 180º. In practical transformers there is small amplitude difference and the phase difference deviates from 180º (see **Figure 19**). Amplitude unbalance is

defined as:

Amplitude unbalance in (dB) = 20 log10 ($|V_2|/|V_3|$)

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

Test Characterization of Transformers
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 50 ohms.

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 50 ohms, impedance transformation is essential to do an accurate measurement. One method is to use resistive matching pads at the secondary[1] 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.

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.

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.

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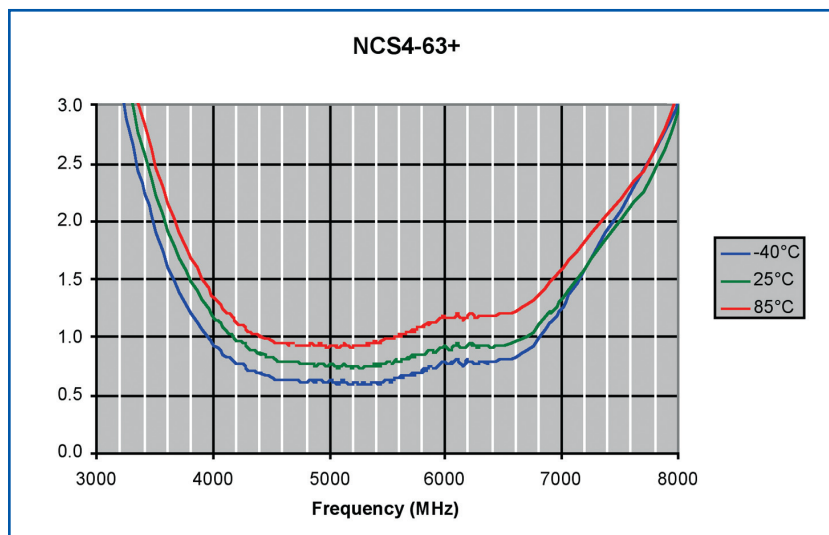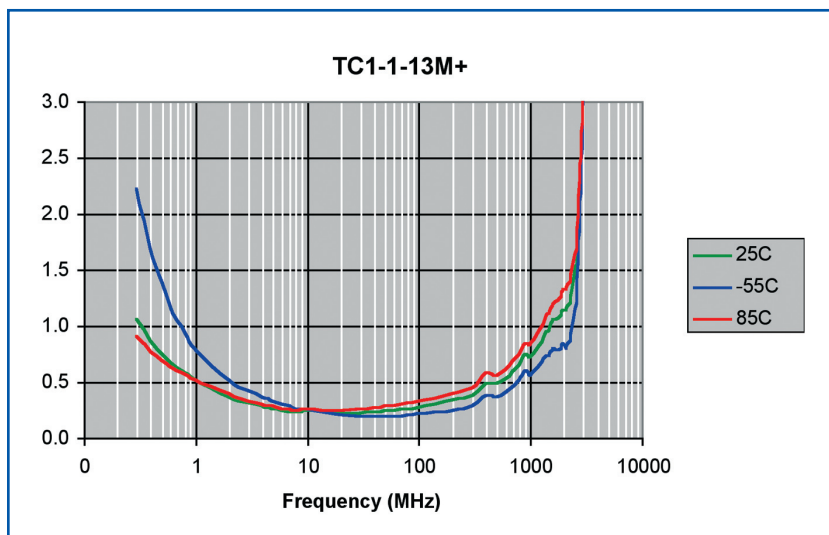
Figure 16: Insertion Loss vs. frequency of core-and-wire transformer

Figure 17: Insertion Loss vs. frequency of an LTCC transformer

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.

Summary

This application note 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.

References

1) Mini-Circuits Application Note, "How RF Transformers Work", http://www.minicircuits.com/pages/pdfs/howxfmerwork.pdf

2) Nathan R. Grossner, "Transformer for Electronic Circuits", McGraw-Hill Book Company, Second edition, 1983

3) R.Setty, "Push-pull amplifiers improve second-order intercept point", RF Design, P76, Nov 2005

4) Mini-Circuits website, http://www.minicir-

Table I: Summary of Transformer Configurations

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		Balnced to balanced transformer	10 to 2200	1.5 to 2	Good	No	Up to 0.25W	YES	--	YES

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cuits.com/cgi-bin/ modelsearch?model=hela-10, click link "Data Sheet"

5) Dorin Seremeta, "Accurate Measurement of LT5514 Third Order Intermodulation Products", Linear AP note 97-3

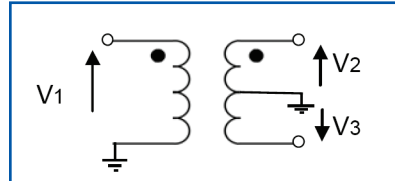6) "Transformers RF/IF", Mini-Circuits web page http:// minicircuits.com/products/ transformers.html
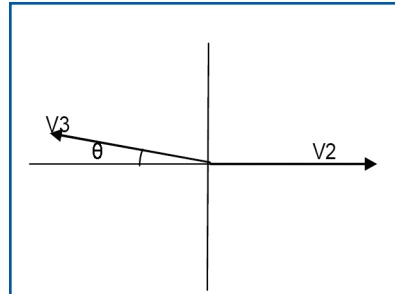

Figure 18: Unbalance in Transformer

Figure 19: Unbalance- Polar representation