# Application Note on Planar Baluns

## <u>Introduction</u>

This note is restricted to a specific type of planar balun structure shown in Figure 1. The red and blue represent two different metal layers. Cyan is the via associated with those layers. This type of balun can be considered as two differential inductors (a primary and a secondary) inter-woven in such a way to provide single-ended to differential conversion and/or impedance transformation. Figure 2 shows the balun in Figure 1 decomposed into the primary differential inductor on the left, and the secondary on the right. Physical descriptions and constraints of these baluns are further elaborated in **Section 1**.

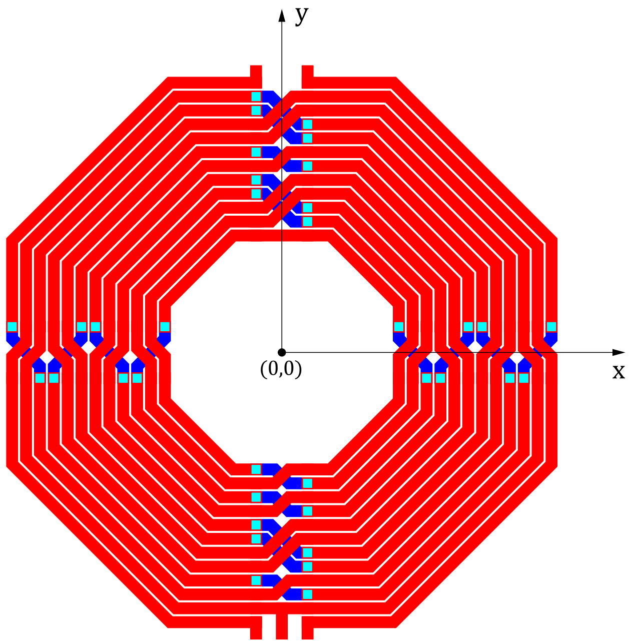



Figure 1: Typical Planar Balun

Depending on the desired number of turns, turn ratio, and center-tap location, visual analysis of the balun function can be difficult. For example, can you easily

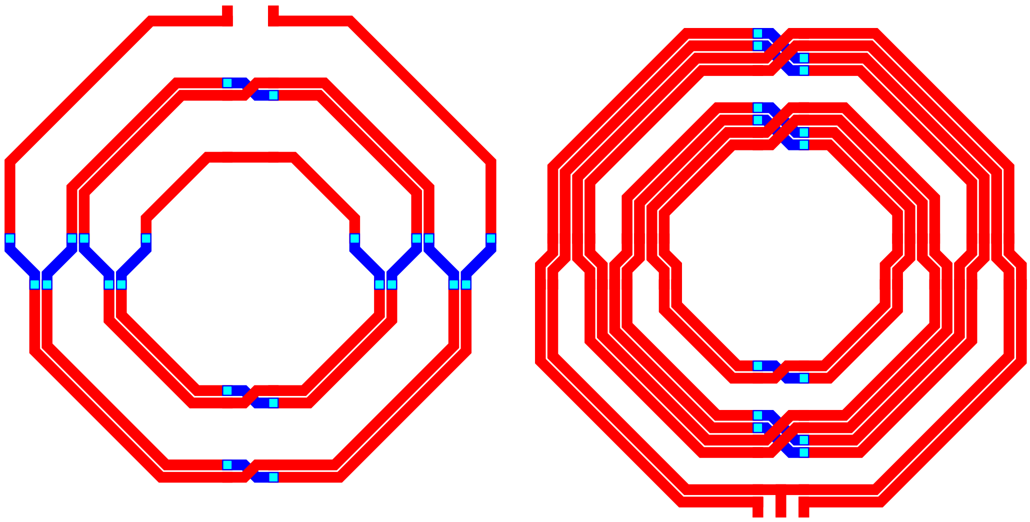


Figure 2: Decomposing the balun of Figure 1 into two differential inductors

tell what the transformation ratio is for the balun shown in Figure 1? Are there multiple ways to achieve the same turn ratio while having a more convenient center-tap location? In **Section 2**, it is shown that these structures can be reduced into a graph representation to facilitate their physical analysis and synthesis.

Electrical characteristics and analysis of these baluns are not discussed. They are left for those with more in-depth RF(radio frequency) component modelling knowledge and EM(electromagnetic) simulation capabilities.

## <u>Section 1</u>

This section defines the elements used in the construction of planar baluns. These definitions are provided for the use of this note. Other materials on the same topic will surely use different conventions. Along with the definitions, some physical constraints are also described.

### Tracks

The highlighted portion in Figure 3 shows the tracks of the balun from Figure 1. The total number of tracks is the turns in the primary plus the turns in the secondary. All the tracks are on the same metal layer and they are of equal width and spacing. The latter two constraints are not necessary but they will greatly simplify their layout especially if the layout is manually generated. Also in Figure 3, it is observed that the twelve tracks are divided into four equal quadrants.

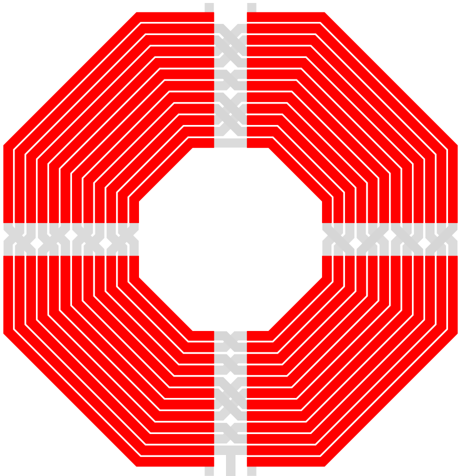


Figure 3: Tracks of a balun

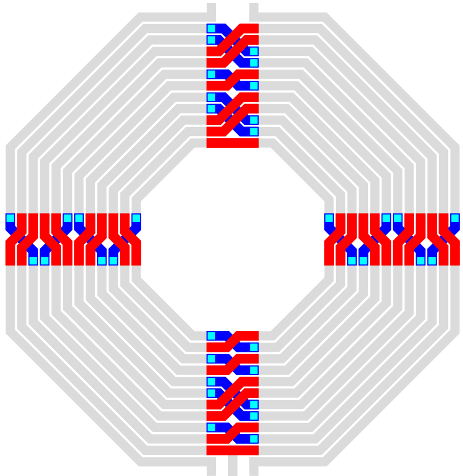
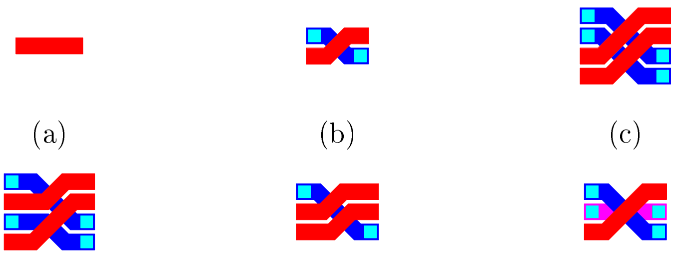


Figure 4: Crossovers of a balun

**Crossovers**

Figure 4 highlights the crossovers of a balun. These structures are responsible for the connections of different tracks to adjacent quadrants. The variants of the crossovers are shown in Figure 5. Figure 5(a) is just a jumper that connects to the same tracks of adjacent quadrants. Figure 5(f) requires three layers of metal and may not be realizable for some process/technology. If the axis of symmetry is the y-axis, then only the crossovers that exhibit symmetry can be placed on the y-axis to connect the tracks of the left and right quadrants. These crossovers are (a), (b), (c), and (f) of Figure 5. Along the x-axis, any crossover structure can be used to connect the upper and lower quadrants. This rule of crossover usage is enforced in Figure 1 or Figure 4. Note that crossovers d and f are not used in the balun shown.



(a) (b) (c)

(d) (e) (f)

Figure 5: Various Crossovers. Not an exhaustive collection

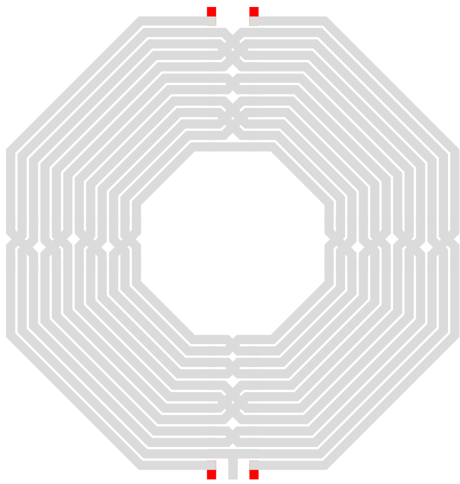


Figure 6: In/Output ports of a balun



Figure 7: The secondary center-tap

**In/Output Ports**
The in/output ports are not physical structures but rather locations where the electrical signals leave and exit the balun. These points are highlighted in Figure 6. The two points of the input pair should be DC connected and located at the extreme ends of the primary differential inductor. The output pair will likewise be the same on the secondary. The two pairs of ports are DC isolated. These characteristics are evident in the decomposition of the balun in Figure 2. Further more, the ports are located along the axis of symmetry (y-axis) and the location of each point in the pair should be mirrored with each other along that axis. The in/ouput ports do not necessarily mirror each other along the compliment axis.

**Center-Tap**
The center-tap is located at the exact halfway point between a port pair. This implies that it is located on the axis of symmetry. In Figure 7, the center-tap location for the secondary is highlighted. The center-tap is usually only used on the differential inductor (or the winding) where the port pair exhibit differential electrical signaling. If the balun is used to transform balanced differential impedance to another, then both primary and secondary center-taps can be utuilized. This is possible since the center-tap location is a virtual ground for differential signals. However, due to the location of the primary center-tap of Figure 1 or 7 (not explicitly shown), a third layer of metal may be needed.

**Section 2**

So far, all the baluns shown are represented by the actual physical layout. In this section, it is shown that the baluns previously described and be reduced to sets of vertices and edges. Figure 8 shows the method of reduction. The tracks

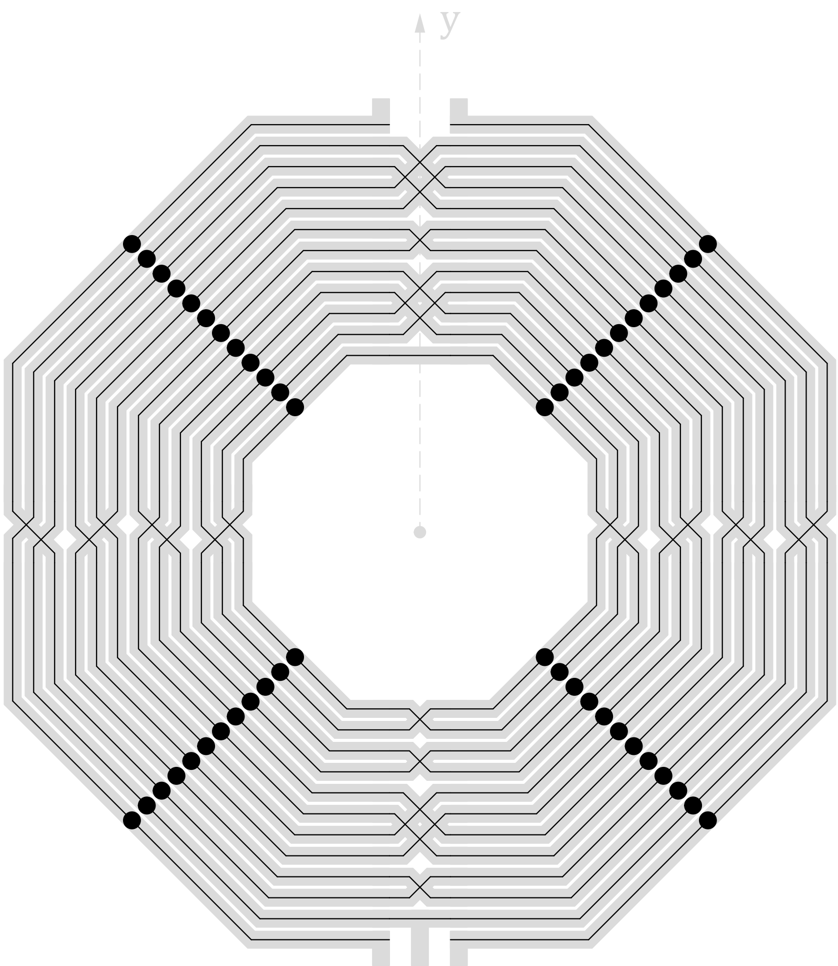



Figure 8: Representation of the tracks as vertices and crossovers as edges

of the four quadrants can be represented as individual vertices and the crossover connections as the edges. Since the balun exhibit symmetry along the y-axis, the connected vertices can be folded from right to left leaving only an upper set and a lower set of vertices. The resulting graph is shown in Figure 9.

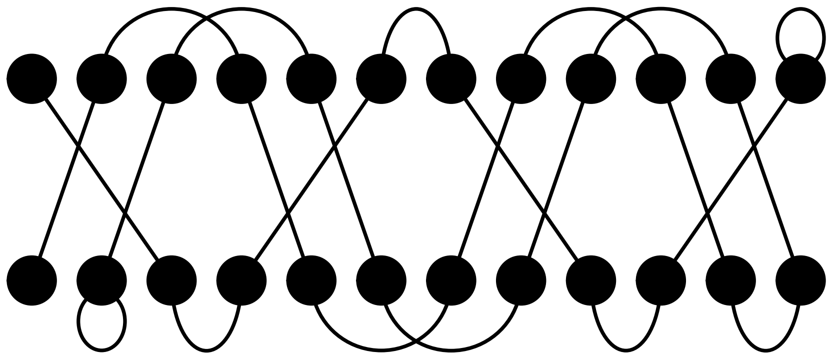
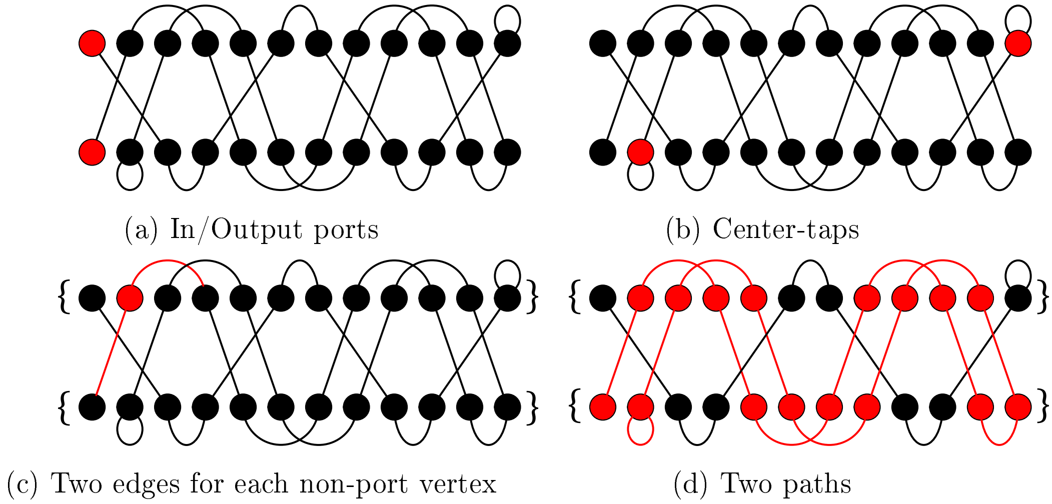


Figure 9: Simplified representation of the balun of Figure 1 or Figure 8

Some key observations and rules can be generalized from the graph representation of Figure 9.

- Each vertex except the two on the far left contains two edges. These one edge vertices are the in/output ports. See Figure 10(a).
- Following the path that starts from a port, the path will end on a vertex with a self loop. These vertices represent the tracks where the center-taps are located. See Figure 10(b).
- If the upper and lower rows of vertices form two ordered sets, each vertex with the exception of the port vertices will have one edge to a vertex in its own set and one edge to a vertex in the other set. See Figure 10(c).
- If correctly designed, there are only two paths and all vertices will have the edges as described. See Figure 10d where there is a red path and the black path.
- The number of vertices in a path that belongs to the same set is the number of turns in that path of the balun. In Figure 10(d), the upper set and the lower set have eight red vertices and four black vertices. The turn ration is 8:4 or 2:1.

The aforementioned turn ratio is just a way to account for the physical number of loops in the balun. Because the circumference of the loops are not commensurate, the resulting turn ratio may not exhibit the expected electrical characteristics.



(a) In/Output ports

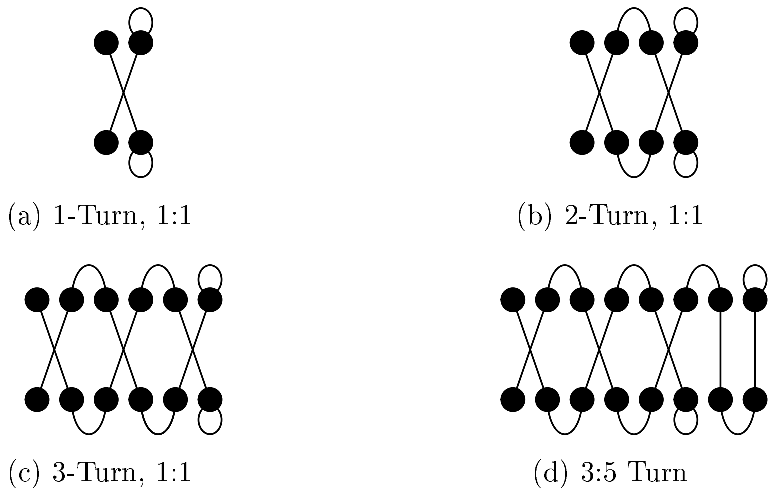
(b) Center-taps

(c) Two edges for each non-port vertex

(d) Two paths

Figure 10: Observations on graph representations of planar baluns

A very common balun topology uses only the crossovers of Figure 5(a) and Figure 5(b). Graph representations and their equivalent physical layout are shown in Figure 11 and Figure 12. The baluns in Figure 11(a) to (c) have the same number of turns on the primary as the secondary and therefore they are 1:1 baluns. Additional turns can be added to any winding and this is shown in Figure 11(d). From these figures, it is shown that an odd number of turns in a winding will move the center-tap location to the opposite side of the x-axis of its corresponding port. These baluns will be designated as the "X" type due to the resemblance to the crossover.



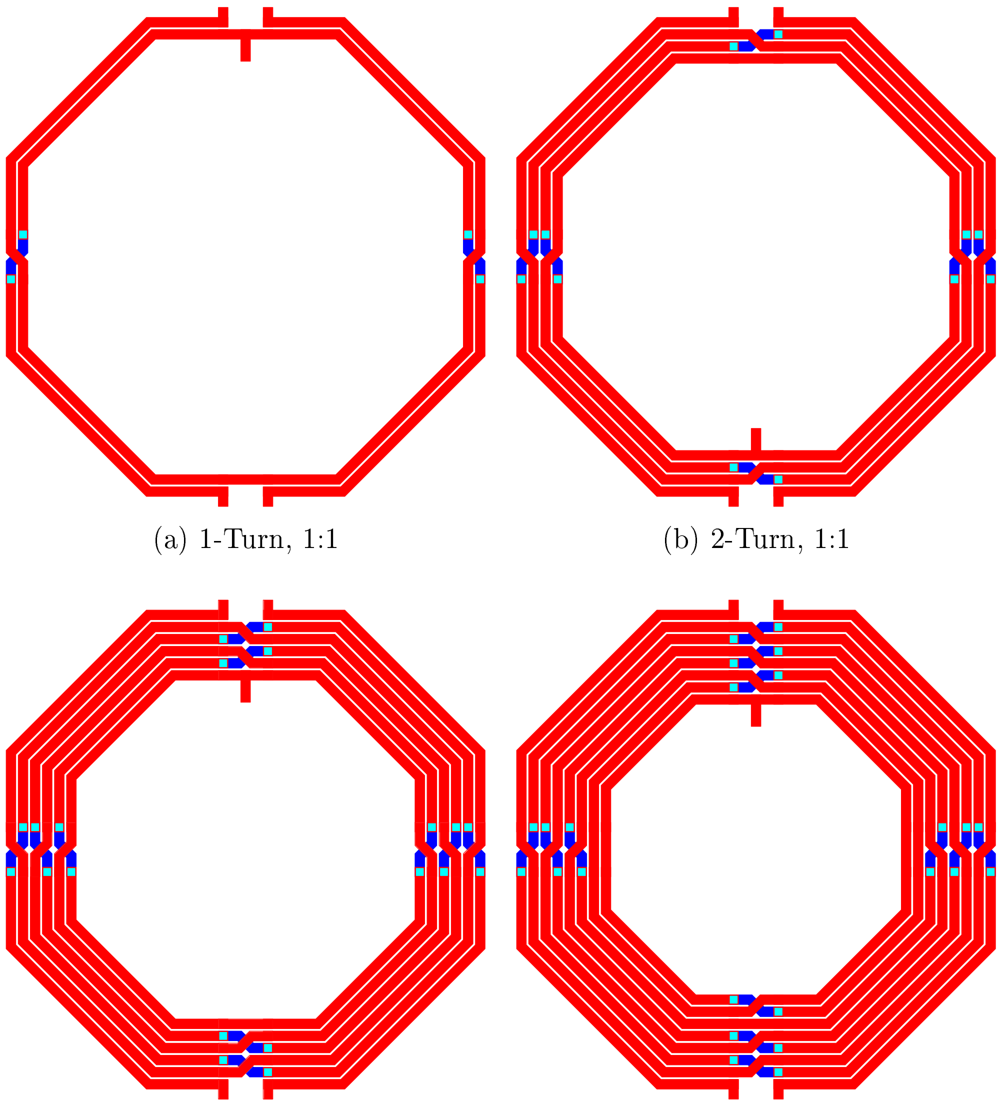
(a) 1-Turn, 1:1

(b) 2-Turn, 1:1

(c) 3-Turn, 1:1

(d) 3:5 Turn

Figure 11: Graphs of baluns using crossovers (a) and (b) of Figure 5



(a) 1-Turn, 1:1

(b) 2-Turn, 1:1

(c) 3-Turn, 1:1

(d) 3:5 Turn

Figure 12: Respective layouts of baluns of Figure 11

The balun shown in Figure 11/12(d) is a commerically available part from STATSChipPAC [1], a passive integrated devices (IPD) vendor. An image of their 3:5 turn ratio balun is shown in Figure 13.

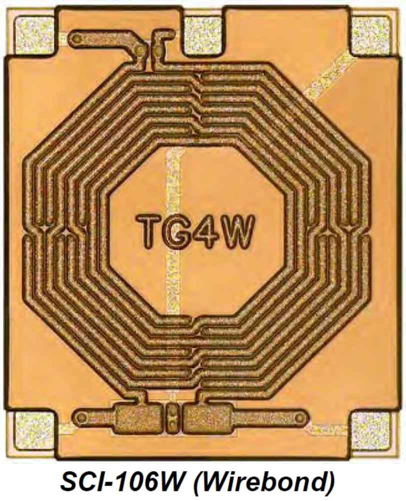
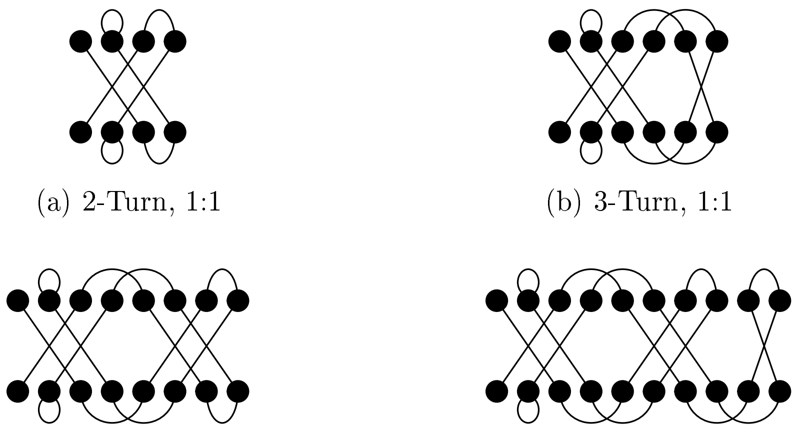



Figure 13: STATSChipPAC balun SCI-106W

In the previous balun topology, the center-tap location is at the inner most turn of each winding. If we also incorporate the crossover of Figure 5(c), then the center-tap location can be relocated to the 2nd most outer turn. Figure 14 shows some typical configurations of these baluns in graph form and in Figure 15, their respective layouts. Again, if the number of turns in a winding is odd, the center-tap location is on the opposite side of the x-axis of the corresponding port. Also, if the turn ratio is not 1:1, then each winding should only have an even number of turns. These baluns are designated as “XX”.



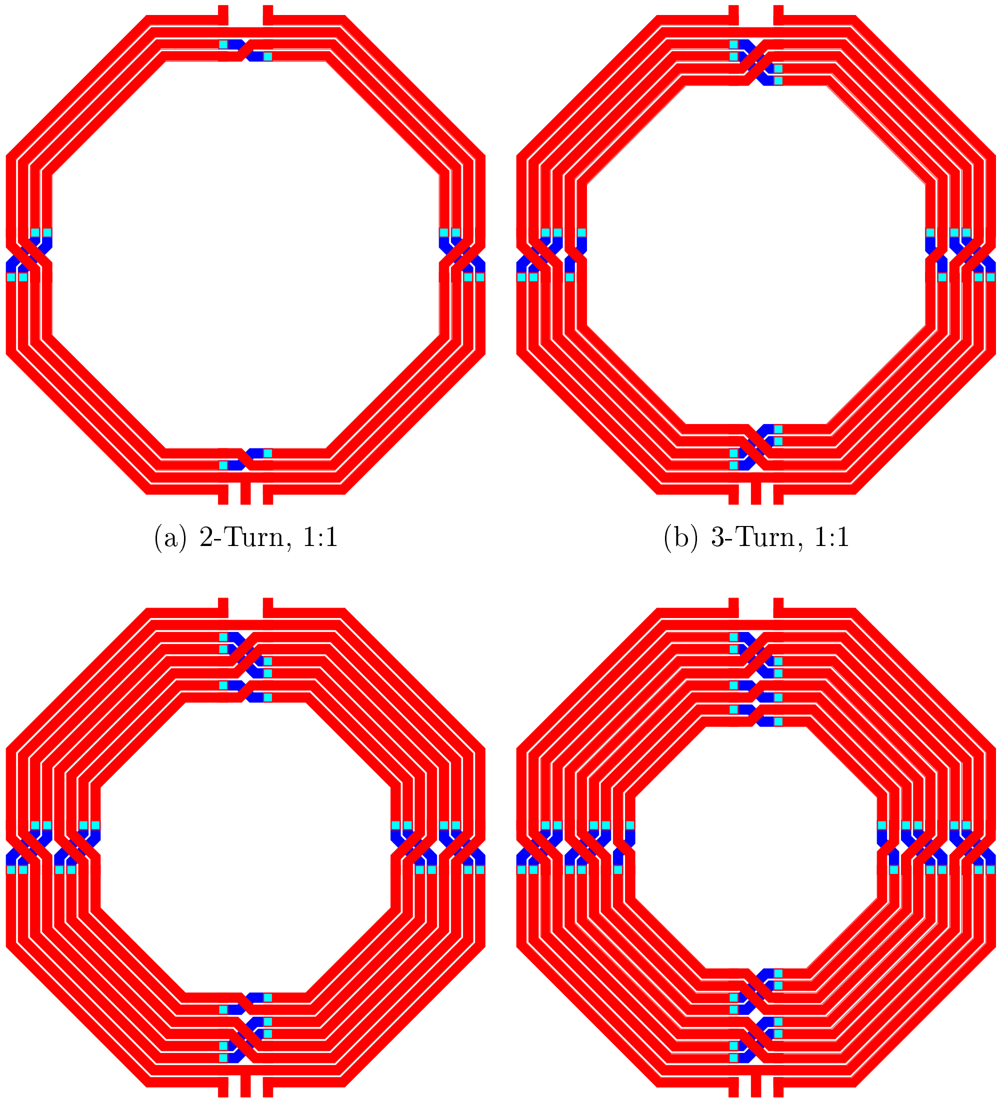
(a) 2-Turn, 1:1

(b) 3-Turn, 1:1

(c) 4-Turn, 1:1

(d) 4:6 Turn

Figure 14: Graphs of baluns using crossovers (a), (b), and (c) of Figure 5



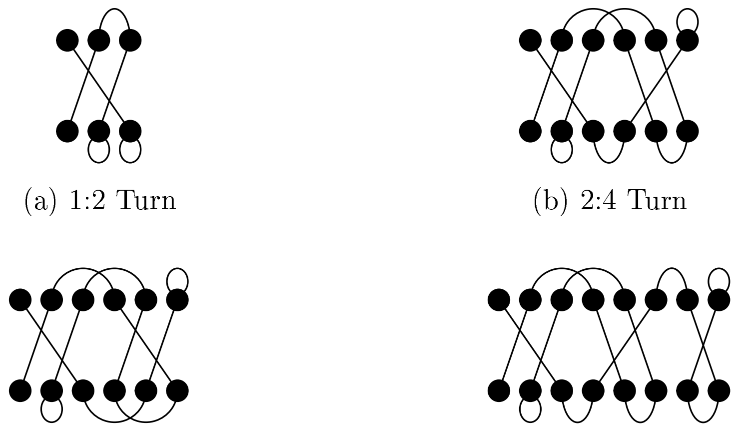
(a) 2-Turn, 1:1 (b) 3-Turn, 1:1

(c) 4-Turn, 1:1 (d) 4:6 Turn

Figure 15: Respective layouts of baluns of Figure 14

Although the previous balun configurations support unequal turn ratios, the way which the primary and secondary windings are interwoven, they may not yield the desired electrical results. For example, if a 2:4 turn ratio is desired, and using only the crossover of Figure 5(b), the distribution of the tracks from outermost of the top left quadrant would be P (primary), S (secondary), P, S, S, and S. Ideally, the distribution of tracks between the primary and the secondary should reflect the turn ratio. In this case, that would be P, S, S, P, S, and S. A variant of this distribution can be achieved if the balun also incorporates the crossover of

Figure 5(e). Figures 16 and 17 show the graphs and layout of some common balun configurations utilizing this crossover. Figure 16(b) shows the 2:4 turn where the distribution of windings is P, S, S, S, S, and P. Figure 16(c) shows an alternate way to connect a 1:2 balun but cannot not be expanded into a 1:2 with more turns. Figure 16(d) shows that 1:1 baluns are also possible using the crossover of Figure 5(e) but perhaps electrically less desirable than the previous topologies. It is observed that for 1:2 baluns of this type, the center-tap of the higher turn winding is located on the 2nd outermost winding while the center-tap of the lesser turn is always at the inner most. Again, the location of this center-tap crosses the x-axis depending on odd or even turns. These baluns are designated as "XI".



(a) 1:2 Turn

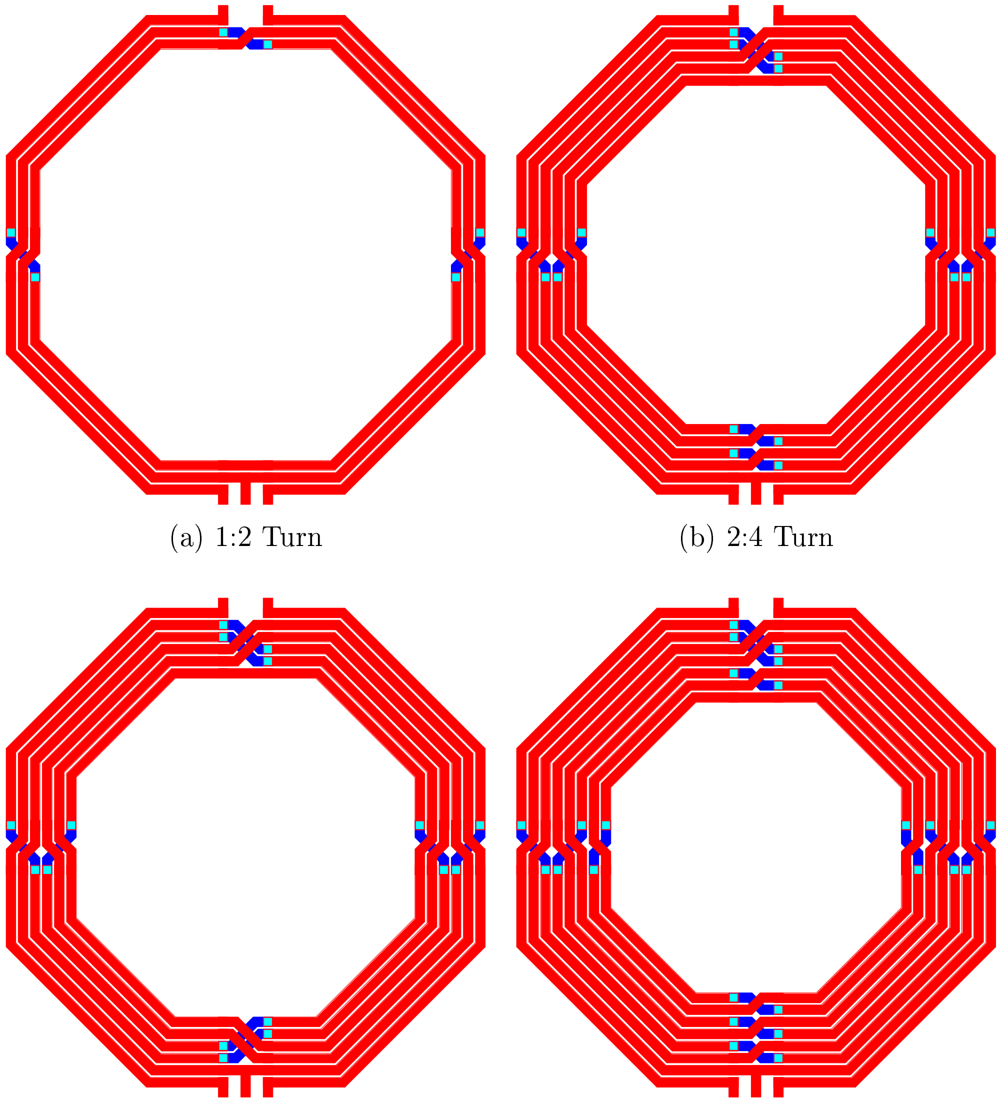
(b) 2:4 Turn

(c) 2:4 Turn non-expandable

(d) 4-Turn, 1:1

Figure 16: Graphs of baluns using crossovers (a), (b), (c) and (e) of Figure 5

Figure 18(a)-(b) shows a commercially available 1:2 balun from Integrand [2] realized using the crossover of Figure 5(e). This configuration is the same as in Figure 17(b) when expanded by three addtional tracks. The equivalent graph representation is shown in Figure 18(c). If this balun was expanded by three additional tracks, the result would be the balun shown in Figure 1.



(a) 1:2 Turn

(b) 2:4 Turn

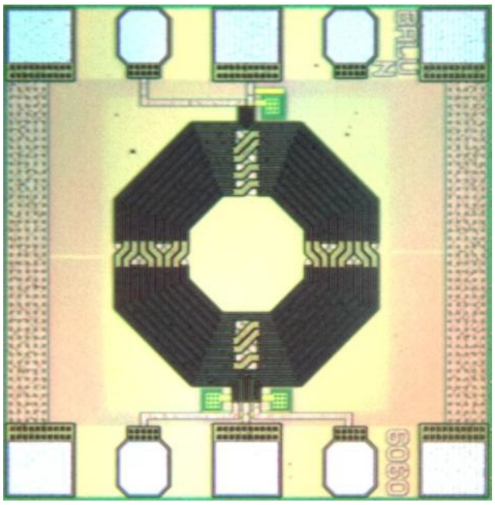
(c) 2:4 Turn non-expandable

(d) 4-Turn, 1:1

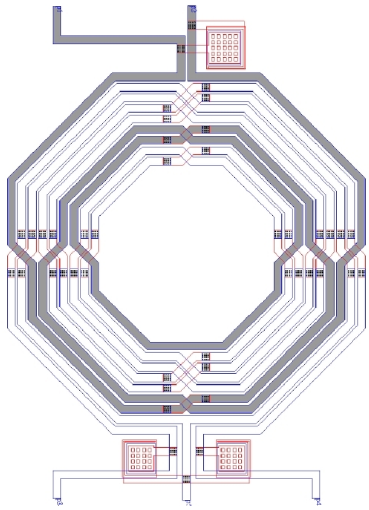
Figure 17: Respective layouts of baluns of Figure 16

## <u>Conclusion</u>

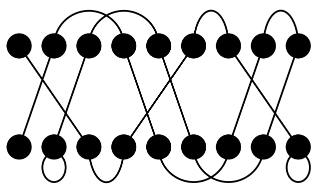
The definitions and restrictions of the components of a planar balun was detailed in **Section 1**. As the number of turns or windings grow, it becomes more difficult to visualize the functionality of the balun such as its transformation ratio. Also, differrent balun topologies yielding the same turn ratio may have different electrical characteristics. Therefore, a simple method of balun representation is



(a) Die photo



(b) GDS with primary shaded



(c) Graph representation

Figure 18: Integrand balun with 3:6 turn ratio

needed for synthesis and exploring various topologies. In **Section 2**, it is shown that the baluns described in **Section 1** can be reduced to a much simpler representation of vertices and edges to facilitate their analysis and synthesis. Furthermore, some common forms of these baluns and commercially available parts were explored.

# References


[1] STATSChipPAC, IPD Products Databook,
`http://www.statschippac.com/documentlibrary/IPD_Databook_2nd_ed.pdf`

[2] Integrand, Synthesis of Optimal On-Chip Baluns,
`http://www.integrandsoftware.com/papers/cicc07_presentation.pdf`