

Electromagnetic Modeling and Application of Conical Coils

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[Summary]

Conical coils used in RF / Microwave and mmWave systems have extremely ultra-wideband electrical responses and are commonly attached to transmission lines to bias microwave devices. These coils have traditionally been designed experimentally without the aid of modern 3D electromagnetic simulators due to the difficult model creation process. Using modern 3D Electromagnetic simulators with scripting capabilities, a structural model of conical coils can be created and their electrical properties determined.

1 Introduction

Conical coils, sometimes called Tapered Coils or Tapered Polyiron Coils (TPCs), are ultra-broadband microwave inductors. Typical applications include bias coils for injecting current into a circuit without disturbing the impedance of a transmission line and as elements in a filter structure. Conical coils have been commercially available for more than a two decades. Several vendors have both flying-lead and Surface Mount Technology (SMT) pick and place coil options with different current handling capabilities, inductance values, physical size and upper and lower frequency limitations¹⁻³⁾. Another product integrates a conical coil with a capacitor to form an integrated SMT broadband bias-T⁴⁾. Conical coils are not limited in their use to the microwave frequency spectrum but can easily extend operation in integrated assemblies well into mmWave frequencies⁵⁻⁶⁾.

Prior to the commercialization of conical coils, broadband bias coils were typically wound on a constant diameter mandrel with either air, ceramic or a magnetic material as its core. Another common broadband inductor is the wire-wound ferrite core toroid type. Most of these coils do not work well over a broad frequency range. The problem is inter-coil capacitance. This capacitance resonates with the coil inductance and produces a “glitch”. This glitch is caused by the self resonant frequency (SRF) of the coil and is often the high frequency limitation. A low capacitance is critical to high frequency performance. Generally, the larger the inductance of the coil, the lower the SRF. A coil with thick wire, large diameter and many turns will have a relatively low SRF and as compared to a coil with small wire, small diameter and only a few turns. As the turns are reduced to zero, the inductor becomes a distributed element and operates over a very

limited frequency range. An example is a quarter wavelength shorted bond-wire.

Resonant glitches due to inter-coil capacitance are especially pronounced when the diameter of the coil is constant. In this case each turn and its associated inter-coil capacitance resonates at the same frequency. One approach in increasing bandwidth of a constant diameter coil and reducing glitches is to put a resistor in parallel across the coil or use resistance wire to form the coil. Unfortunately, this reduces the Q of the inductor making it unusable for filter structures and also limits the current handling capability due to the heat generated. Another method in reducing the inter-coil capacitance is to taper the coils diameter over its length. This taper forms the conical coil. Each turn and its associated inter-coil capacitance is slightly different and the resonances are much less pronounced over a very large bandwidth and to very high frequencies. The tapered shape minimizes the effects of inter-turn capacitance and the polyiron both increases the inductance at low frequencies and reduces the Q at high frequencies. The very small end of the conical coil causes minimal parasitics at the high frequencies while the larger diameter provides more inductance at low frequencies.

Conical coils have traditionally been designed experimentally without the aid of modern 3D electromagnetic simulators. There are significant benefits in creating the parametric 3D electromagnetic model of a conical coil: 1) model changes to explore “what-if” scenarios are easily generated. 2) “cut-and-try” experimenting is eliminated. 3) design and development of conical coils proceeds at a much faster rate with high degrees of first-pass success.

2 Model Description

2.1 The need for scripting

Creating a 3D model that includes many repetitive geometric elements is best done programmatically instead of creating each element manually through the modelers graphical user interface (GUI). Most 3D EM simulation tools have an application programming interface (API) which allows structural modeling through the use of macros scripts⁷⁾. Macro scripts can contain parametric values exposed to a dialog box which allows users of the macro to manipulate the default values. Not only can the script be used to create the 3D structure but it can also include setup details such as: boundary and symmetry conditions, ports and materials. The key benefit in using a structure macro is its reuse and saves an enormous amount of time in the model creation and model change process.

Figure 1 shows a Conical coil dialog generated by the structure macro. The Conical coil is mounted in shunt to a Microstrip transmission line. The wire from the wide end of the coil leads to an electric wall boundary (i.e. a short or ground). Many of the parameters in the dialog are self-explanatory so only a few will need further explanation.

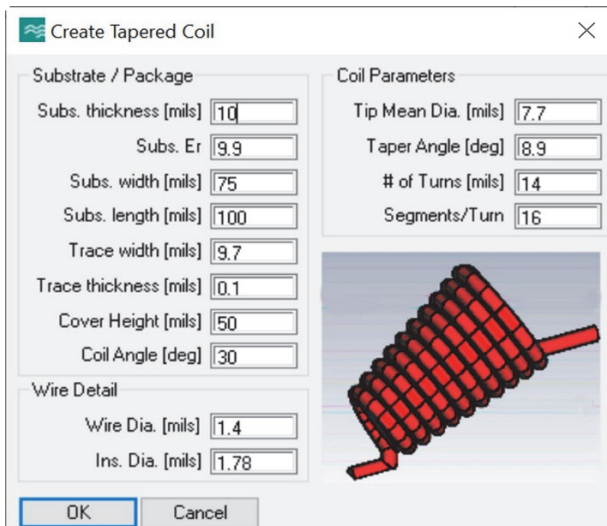


Figure 1 Conical coil structure macro dialog

2.2 Dialog parameters and definitions

- Coil angle is the angle formed by the coils centerline with respect to the substrate surface (range: 0 to 180°)
- Wire diameter and Insulation diameter corresponds to AWG 47 magnet wire with heavy build⁸⁾.
- Tip mean diameter is the wire center-to-center diameter of the first wire turn at the coils tip.

- Taper angle is the angle formed by the coils centerline with respect to coils tip-to-end difference in radius (range: 0 to 90°)
- # of turns defines the total number of turns from the coils tip-to-end (Figure 1 coil image shows 10 turns)
- Segments per turn defines the number of straight wire segments in one coil wire turn (suggest ≥ 16)

The castable iron-core material is not a selection in the dialog, although the model includes castable iron-core material Eccosorb CF-117⁹⁾ within the macro script. The castable iron core material properties are highly dependent on the weight ratio of iron powder to epoxy as well as the properties of the individual components. Castable iron-core material models are characterized from actual conical coil measurements using an existing iron powder and epoxy formulation. Another detail not included in the macro dialog is the coil tip wire length. The distance of the coil tip to the trace edge is critical and should be minimized. The coil tip wire length setting within the macro is 2-mils. This parameter was excluded from the dialog for simplicity. Figure 2 shows the structure generated by the macro using parameters listed in Figure 1.

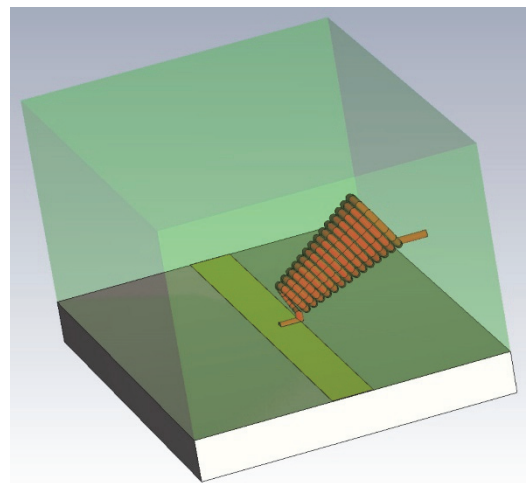


Figure 2 Conical coil structure generated from macro

2.3 Model Construction

The core element in constructing the conical coil is the discrete segment 3D polygon as shown in Figure 3. This tapered helical coil shape forms the basis of the coil model. Forming the polygon model using discrete segments eases the programmatic model creation. Figure 3 shows each turn having 8 segments and this was chosen only for clarity. Increasing the number of segments per turn to 16, for example, more

closely approximates an ideal smooth circular turn. A continuously smooth circular contour can be created but this tends to create meshing issues. The number of segments per turn that reasonably approximates a continuous circular turn was chosen to be 16. Increasing the number of segments does increase model accuracy at the expense of increased mesh density and longer simulation times.

The 3D polygon defines a path to which the copper and insulation can be swept over forming the insulated wire. The castable iron-core material is simply modeled as a cone with similar tip and end radii of the 3D polygon model.

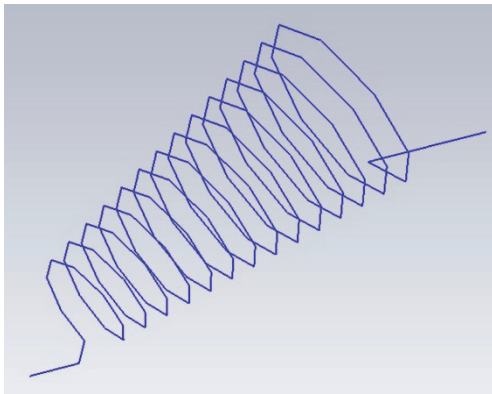


Figure 3 3D Polygon model of Conical coil, (14 turns, 8 segments per turn)

2.4 Boundary Conditions

In Figure 4, electric walls are defined on the bounding box sides and box bottom. This condition shorts one end of the coil forming the coil-in-shunt circuit model. An open boundary is defined on the top of the bounding box and helps minimize box resonances. Loss was included for all materials and also helps to minimize resonances over a broad range of simulation frequencies.

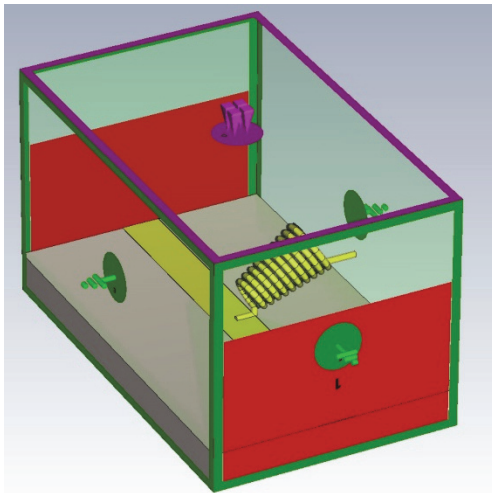


Figure 4 Conical coil model boundary conditions

3 Simulation Results

3.1 Inductance vs. Number of coil turns

For the 3D models simulated, their two port parameters were matched to that of an ideal lumped shunt inductor using a circuit simulator¹⁰. The inductance of each conical coil model was indirectly determined using this process. Figure 5 shows a plot of inductance vs. number of turns of each conical coil simulated. The data points were fitted to a power equation as shown in (1).

$$L[nH] = 0.1482 * \text{Number of turns}^{2.2725} \quad (1)$$

In Figure 5, there are only a few sparsely located points above 15 turns. Above approximately 15 turns, the 3D model starts to become more complex with the number of mesh cells and simulation times increasing significantly. Only a small number of points is needed to form the power equation formula and still achieve a reasonable error between the formula and the 3D modeled points. The percent error of the derived power equation formula (1) with respect to the actual 3D modeled coil inductances is shown in Table 1. The equation can be used to predict the coil inductance for a given number of turns without the need to use a 3D simulator. Furthermore, for coils having greater than 15 turns, for example, it may be unrealistic to use a 3D Electromagnetic simulator due to the high number of mesh cells and long simulation times as stated earlier.

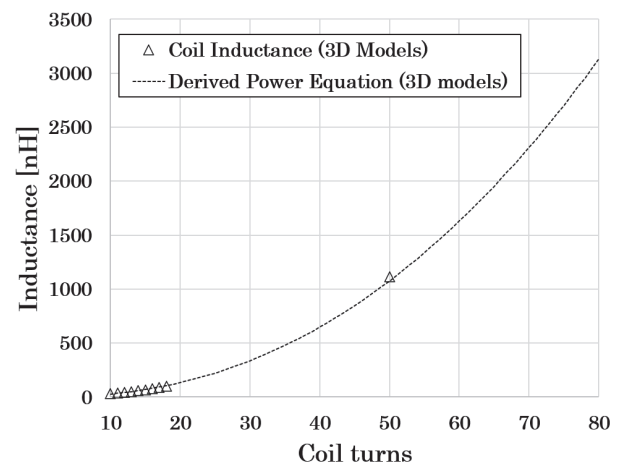


Figure 5 3D Model Coil inductance vs. number of turns

Table 1 Percent Error of 3D Equation Derived Inductance Values against inductance equation (1)

Coil Turns	L [nH]	L [nH], Eq. (2)	% Error
10	29.0	27.8	4.3
11	35.5	34.5	2.9
12	43.0	42.0	2.3
13	50.5	50.4	0.2
14	58.5	59.6	1.9
15	68.0	69.7	2.6
16	78.5	80.8	2.9
17	90.5	92.7	2.4
18	101.5	105.5	4.0
50	1115.0	1075.9	3.5

4 Coil Assembly and Measurements

4.1 Assembly

To verify the taper coil model, actual tapered coils were built and tested. The built coils were designed according to the physical wire and coil parameters as shown in Figure 1. A castable absorber with properties similar to Laird CF-117 was used. A series of coils with 10, 11, 12, 14, 15, 16, 17, 24, 25 and 50 turns were assembled.

4.2 Measurements

Each coil was mounted to a 1.2 cm long, 10 mil thick alumina substrate with a 50-ohm transmission line as shown in Figure 6. The wire leading from the wide end of the coil is soldered to the backside of the substrate providing a short. A Universal Test Fixture¹⁰⁾ (UTF) was used to hold the substrate and to facilitate 2-port S-parameter measurements. The coil inductance was indirectly found by matching the measured 2-port S-parameters to that of a shorted shunt inductor circuit model in AWR MWO⁹⁾. Inductance results are shown in Figure 7 along with the derived power equation curve using equation (1). The percent error of the built coil inductance values are shown in table 2 with percent errors below 15%. Many of these coils do not have a perfect whole integer number of turns which partially contributes to the error. This inductance power equation formula can help determine the number of turns required for a desired inductance value assuming a linear coil taper.

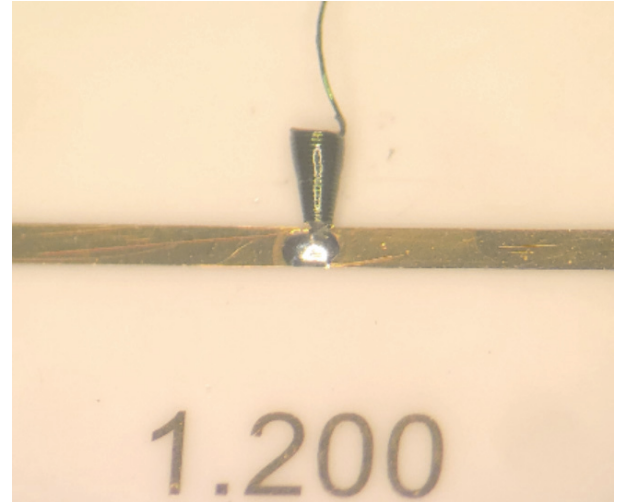


Figure 6 18-turn coil assembly mounted to 10-mil thick alumina substrate

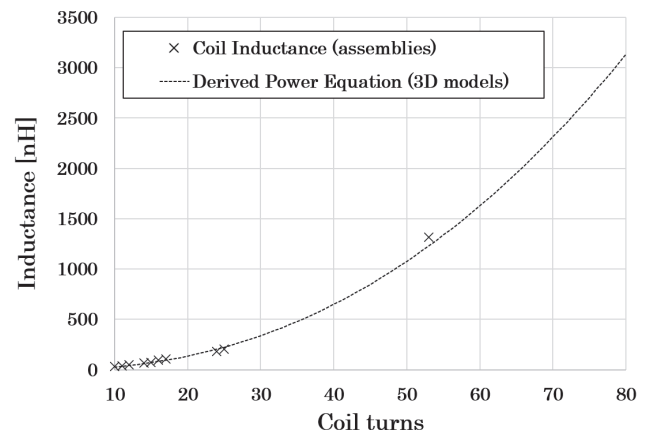


Figure 7 Coil inductance (assemblies) vs. number of turns

Table 2 Percent Error of built coil assembly inductance values with respect to inductance equation (1)

Coil Turns	L [nH]	L [nH], Eq. (2)	% Error
10	31.5	27.8	11.9
11	39.5	34.5	12.7
12	49.0	42.0	14.3
14	63.5	59.6	6.1
15	72.5	69.7	3.8
16	93.0	80.8	13.2
17	106.5	92.7	13.0
24	180.5	202.9	12.4
25	203.0	222.7	9.7
53	1315.0	1228.2	6.6

Similarly, the Quality Factor (Q) of each coil was found by matching the measured S11 and S21 result to that of the circuit model S11 and S21 results at 10 MHz. The circuit model

used an inductor-with-Q element to facilitate the Q parameter adjustment at 10 MHz. DC Resistance measurements were made on each substrate mounted coil and represent the copper wire resistance. Figure 8 shows a plot of coil Q and resistance vs. number of coil turns.

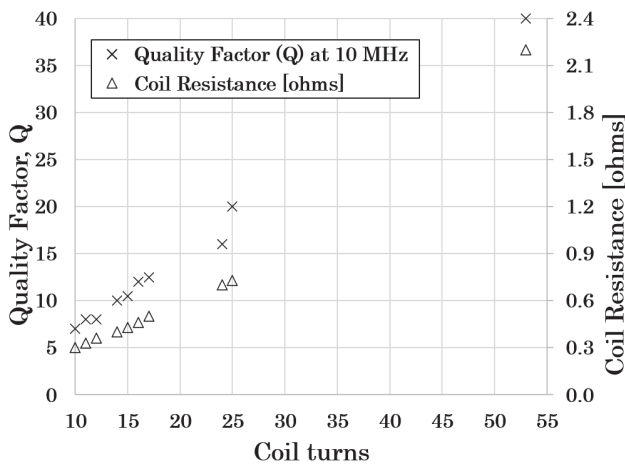


Figure 8 Quality Factor (Q) and Resistance vs. coil turns

The inductance of the coil assemblies matched reasonably well with the model. This implies the castable absorber material used has properties which closely match that of Laird CF-117 castable absorber. If, by chance, the inductance values of the assemblies didn't match the model, then the castable absorber permeability used in the coil model could be changed as a means to indirectly characterize the castable absorber permeability of the assemblies.

5 Application

5.1 Broadband Contiguous Diplexer Design

3-port contiguous diplexers can be formed by connecting two singly-terminated, Butterworth high and low pass networks. At the crossover frequency, the S21 responses of both the high and low pass branches will equal 3 dB. At this frequency, the common port match is perfect. In practice, L and C values can have $\pm 20\%$ and $\pm 10\%$ value tolerances respectively along with other parasitics present and response characteristics will not be perfect. In addition, it is extremely difficult to achieve a resonant-free inductor from DC into millimeter-wave frequencies unless a conical coil is used. Figure 9 shows a 1st order 150 MHz contiguous diplexer with an ideal capacitance and inductance of 22.0 pF and 54.8 nH respectively. To get an idea how the diplexer s-parameter response curves will change with part tolerances, a uniform distribution yield analysis was performed by allowing the L and C values to change by $\pm 20\%$ and $\pm 10\%$ respectively. The

yield analysis plot is shown in Figure 10. With $\pm 20\%$ L and $\pm 10\%$ C part tolerances, the common port (P1), has a match that is better than 20 dB. Over these tolerances, the crossover frequency falls within the range of 130-170 MHz.

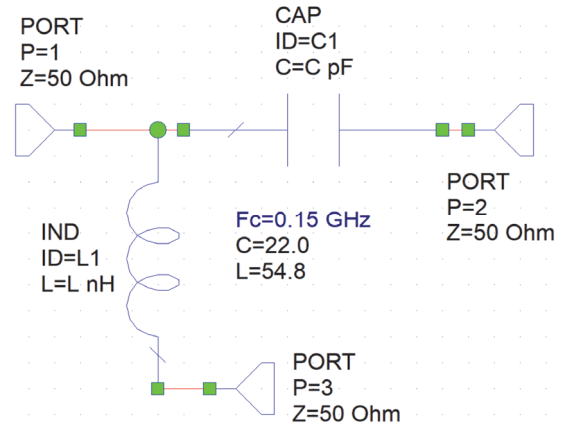


Figure 9 Ideal 150 MHz 1st order Contiguous Diplexer

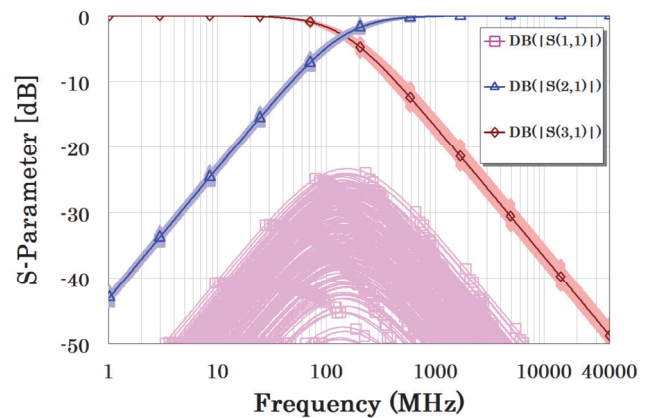


Figure 10 Yield analysis of 150 MHz, 1st order Contiguous Diplexer assuming $\pm 20\%$ L and $\pm 10\%$ C part tolerances

5.2 Broadband Contiguous Diplexer Model

Figure 11 shows a 3D model of the 150 MHz diplexer using a 13-turn conical coil and 22 pF capacitor. The capacitor is chosen as a 10-mil \times 10-mil \times 4-mil single layer type with 10% tolerance. This capacitor mounts onto a 10-mil wide Microstrip trace adjacent to the location where the coil is attached. Gold bondwires or mesh joins the top of the capacitor to the Microstrip trace. The wire leading from the wide end of the coil is soldered to a 50-ohm trace. Simulated transmission and reflection responses are shown in Figures. 12 and 13 respectively.

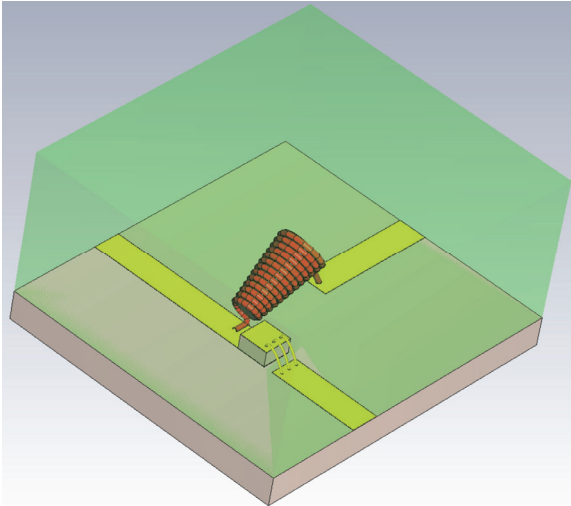


Figure 11 3D model of 150 MHz Broadband Diplexer using 13-turn conical coil and 22 pF single layer capacitor

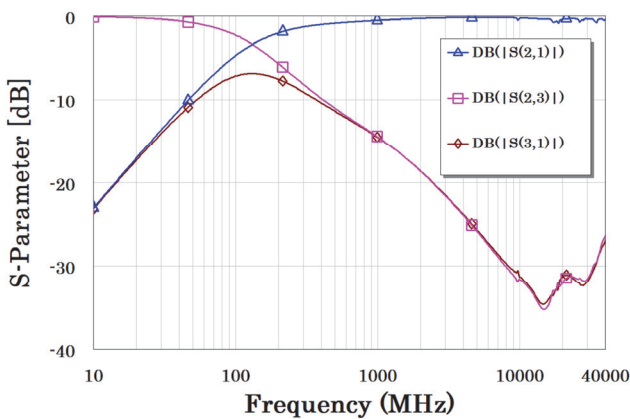


Figure 12 Transmission response of 150 MHz Broadband Diplexer

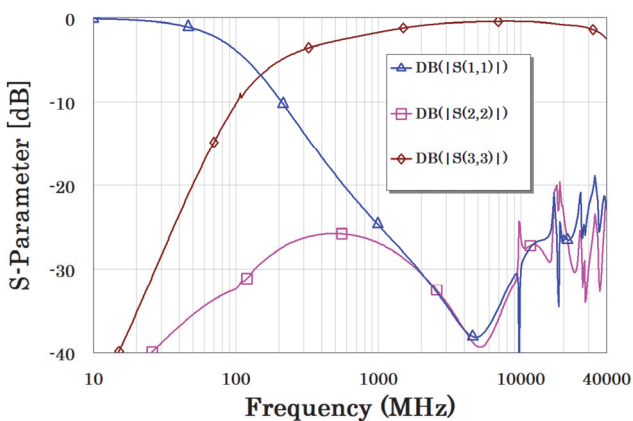


Figure 13 Reflection response of 150 MHz Broadband Diplexer

6 Conclusions

3D electromagnetic structures can sometimes involve significant geometric detail. In these situations, it is not time efficient to manually draw the 3D model and it is usually

better to create the 3D model by using a programmatic script. The conical coil is one example where creating a script to build the 3D model can save a significant amount of time. Exposing model parameters through a user dialog facilitates the generation of 3D models with different features that can be remotely batch-simulated on a cloud-based simulation service.

Not only can conical coils be used as bias elements, but they can also be used as a broadband reactive elements in filter designs. Careful selection of castable polyiron material properties, coil turns, diameters, wire size, etc. can yield a wide range of inductance values.

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