3 GHz Wide Frequency Model of Surface Mount Technology (SMT) Ferrite Bead for Power/Ground and I/O Line Noise Simulation of High-speed PCB

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Abstract

A precise and reliable high-frequency equivalent circuit model of SMT ferrite bead is reported up to 3 GHz. The proposed model is successfully verified with excellent agreement to experiment in terms of magnitude and phase of S-parameter. Two typical structures among a lot of applications using SMT ferrite bead are also studied for the verification of the proposed model. One is when SMT ferrite bead is used in Power Island for DC connection but high-frequency noise isolation. The other is when SMT ferrite bead is used in I/O line of signal and power for EMC purposes. Advanced design system (ADS) from Agilent Technologies and Ensemble from Ansoft are used for simulation.

Introduction

Ferrite bead is one of an extensive range of tools used to mitigate EMI [1]. However, there seem to be difficulties to choose a suitable ferrite bead and simulate high-speed PCB including SMT ferrite bead for EMC purposes.

Ferrite materials are basically nonconductive ceramic materials that differ from other ferromagnetic materials such as iron in that they have low eddy-current losses at frequencies up to hundreds of megahertz [2]. This unique property makes ferrite bead very usefully provide selective attenuation of high-frequency signals that we may wish to suppress from the standpoint of EMC and not effect the more important lower-frequency components of the functional signal [2], [3]. Especially, SMT ferrite bead is preferred in high-speed digital PCB because of compact size and easy assembly [4].

In high-speed and high-density multi-layer PCB, power plane is separated into several sections to prevent sensitive analog circuit from simultaneous switching noise (SSN) of high speed digital circuit. Power Island is also recommended to supply several voltage levels on a board without additional board and to prevent the circuits from electrostatic discharge (ESD) [9]. Especially, the high-frequency noise on a DC power-bus caused by SSN is a primary source of many EMI and SI problems in high-speed digital circuit design [2], [5], [6], [7]. Therefore, to provide DC connection and maintain high-frequency noise isolation, the usage of SMT ferrite bead in Power Island could be one solution. As shown in Fig 1, typical ferrite bead has very low impedance at low frequencies near DC, but high impedance at high frequencies. Those characteristics of ferrite bead can achieve selective high-frequency noise isolation without any damage to very important DC level and lower-frequency functional signal. Also, SMT ferrite bead can be used as a filter with capacitors in Power Island.

Another main application of SMT ferrite bead is I/O line filtering. In high-frequency signal line and high-speed clock line etc. radiated emission, conducted emission, and ringing cause unexpected results. In those cases, single SMT ferrite bead or combination between SMT ferrite beads and capacitors could filter high-frequency noise. Also, very high resistance of ferrite bead at high-frequency relatively increases the external Q value. Therefore, increased Q results in the removal of ringing.

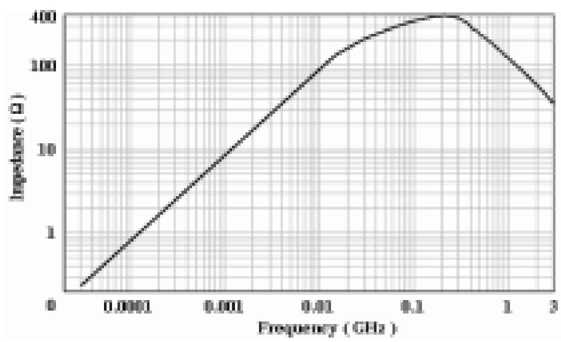
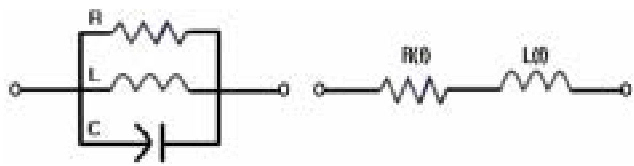


Figure 1. The impedance plot of typical SMT ferrite bead



(a) (b)

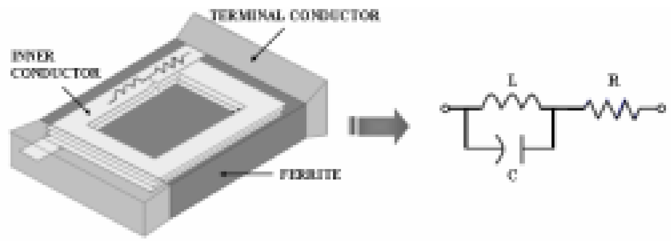
Figure 2. Published previous models of the ferrite bead (a) parallel RLC model (b) frequency dependent RL model

There are several previous models of the ferrite bead as shown in Fig 2. The ferrite bead is described by a parallel RLC model [8] or by a frequency dependent series RL model [2], [9]. Even though those published models are relatively simple, the model can be applied only up to a few hundreds MHz [8]. Also, the impedance of a typical SMT ferrite bead is not well characterized by previous models because previous models doesn't consider frequency dependent characteristic over a wide frequency range. However, the noise frequency of advanced current high-speed GHz digital systems has frequency range well over 1GHz, and as frequency goes up, losses at high frequencies can not be ignored for more accurate and reliable model. Accordingly, the precise and reliable electrical model of the SMT ferrite bead over GHz frequency range is crucially required for practical EMI field engineers for proper design of power supply and noise isolation. Especially, the model is needed for the power/ground and I/O line noise simulation of the multi-layer PCB.

In this paper, new electrical equivalent circuit model of SMT ferrite bead is reported. The frequency dependent characteristics of SMT ferrite bead are considered into the proposed model with lumped elements. The proposed wide frequency model of SMT ferrite bead is well fitted into S-parameter measurement and Impedance up to 3 GHz, and the model is successfully verified with the experiment. The verification of proposed model is made through comparison between model simulation and vendor produced SMT ferrite bead measurement. The model can also be easily embedded into circuit and PCB level power/ground noise simulations. Two typical structures using SMT ferrite bead are also studied for verification of proposed model in real applications.

Proposed Model of SMT Ferrite Bead and Analysis

Fig 3 shows the physical structure of the test SMT ferrite bead used for the modeling and the verification experiments. The simplest model of SMT ferrite bead in Figure 3 can be extracted from the physical structure. R comes from the conductor loss from terminal conductor and inner conductor. L is inductance representing self-inductance of the conductor and internal inductance produced by flux passing through the ferrite material when current passes along the conductor. C is capacitance existing between the inner spiral-type conductors inside the ferrite bead. However, for more accurate and reliable model, losses at high frequencies have to be considered.



(a) **(b)**

Figure 3. (a) The physical structure of the SMT ferrite bead. The test ferrite bead is used for the model extraction and for the verification of the proposed model: Total length of the ferrite bead is 2.0±0.2mm, width of 1.25±0.2mm, height of 0.85±0.2mm, and terminal conductor of 0.5±0.3mm thickness. (b) The simplest RLC model of SMT ferrite bead: R comes from the conductor loss from terminal conductor and inner conductor. L is inductance representing self-inductance of the conductor and internal inductance produced by flux passing through the ferrite material when current passes along the conductor. C is capacitance existing between the inner spiral-type conductors inside the ferrite bead

There are two main factors to cause losses according to the increase of frequency. Skin effect, edge confinement in inner conductor of current according to the increase of frequency results in the increase of sectional resistance. Finally, the increase of sectional resistance causes loss at high frequencies. Also, the loss by the ferrite material coming from the imaginary part of complex relative permeability can not be ignored. Permeability of ferrite material experiences the decrease according to the increase of frequency. The decrease of permeability is very slight in low-frequency band, but after some frequency, permeability shows sharp drop. Finally, sharp drop causes loss at high frequencies.

Fig 4 and Fig 5 show the proposed equivalent circuit model of SMT ferrite bead and dominant path in model according to the operating frequency range respectively. Before parallel resonance of L and C (refer to Figure 3. (b)), path 1 in the proposed model in Fig. 5 is dominant because the inductive characteristic of SMT ferrite bead is dominant. However, after parallel resonance of L and C, path 2 in the proposed model in Fig 5 is dominant because above the resonance frequency, magnetic field from the conductor current is confined dominantly between the inner conductor, and the capacitive characteristic of SMT ferrite bead is dominant. Therefore, losses from skin effect and ferrite material before resonance frequency are represented as R1 and R2, and losses after resonance frequency are represented as R_p. R_{dc} is dc resistance of SMT ferrite bead.

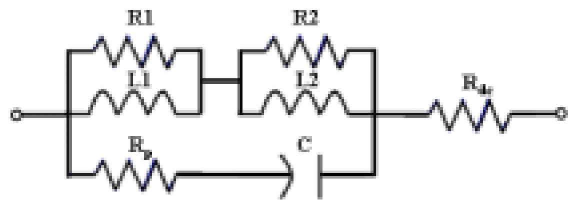


Figure 4. Proposed high-frequency model of SMT ferrite bead: Frequency dependent characteristic, L(f) at frequency range before resonance frequency is expressed with two sections of parallel lumped R and L. Frequency dependent characteristic, C(f) at frequency range after resonance frequency is expressed as series lumped R and C

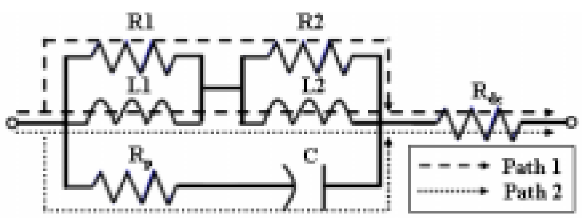


Figure 5. Dominant path in the proposed model according to the operating frequency range. Before parallel resonance of L and C (refer to Figure 3. (b)), path 1 is dominant because the inductive characteristic of SMT ferrite bead is dominant. After parallel resonance of L and C, path 2 is dominant

because the capacitive characteristic of SMT ferrite bead is dominant

Finally, frequency dependent characteristic, L(f) at frequency range before resonance frequency is expressed with two sections of parallel lumped R and L. Although single section of parallel R and L can express the frequency dependent characteristic, but for more accurate and reliable model over wide frequency range, two sections are needed. Frequency dependent characteristic, C(f) at frequency range after resonance frequency is expressed as series connection of lumped R and C.

Extraction Process of Parameter Values and Verification of Proposed Model

To verify the proposed SMT ferrite bead model, a few comparisons were made between simulation results with the model and measurement results with a few vendor produced chip beads. In previous paper [10], the SMT ferrite bead was directly connected to SMA connector, and then 1-port S-parameter measurement was achieved for modeling. However, in this paper, another measurement approach was conducted. SMT ferrite bead was embedded into coplanar type line with lower ground plane, and then 2-port S-parameter measurement was made for modeling. After measurement of coplanar type line with lower ground plane including SMT ferrite bead, to get the characteristic of only SMT ferrite bead, embedded line for measurement in previous measurement which exist in each side of SMT ferrite bead are measured again, and then measured lines are de-embedded from the previous measurement. In this process, Network Analyzer 8753ES and ADS from Agilent Technologies were used for measurement and simulation respectively. The test ferrite bead is a MMZ2012S301A from TDK Corporation. Also, the series L connected to C in previous paper [10] is removed for more simplicity with maintaining accuracy and reliability.

The extraction process of parameter values starts by deciding rough R, L, and C components' values in the model. Inductance, L (L1+L2) and R_{dc} can be calculated from the impedance value at the lowest frequency end. On the other hand, resistance R (R1+R2) representing the conductor loss and the ferrite loss can be obtained simply from subtracting previous determined R_{dc} from the magnitude of the impedance at the resonance frequency. Capacitance, C can be predicted from the pre-determined L value and the resonance frequency. After the rough determination of the R, L, and C values, L is divided by 2 for L1 and L2. R is also divided by 2 for R1 and R2, and then R_p is obtained through optimization process. If the comparison between the plot from the proposed model with the roughly determined L1, L2, R1, R2, R_{dc}, C, and R_p values and the measured plot from the vendor produced SMT ferrite bead does not yield a good agreement, optimization process will be repeated again to get slightly modified values. In this case, the exact modification has to be made with each part of the plot. C and R_p have to be modified with the capacitive part of the plot because those parameters dominantly represent capacitive characteristic of ferrite bead model, while L1, L2, R1, and R2 have to be modified with the inductive part of the plot. It is because those parameters mainly represent inductive characteristic of the ferrite bead model. After those modifications of the parameter values, if the comparison has a reasonable agreement, the model and parameter values are finally determined. Table 1 lists the extracted model parameter values.

Parameter	L1	R1	L2	R2	C	R_p	R_{dc}
Value	1.15μH	250Ω	0.5 μH	60Ω	1.4pF	15Ω	0.05Ω

Table 1. Extracted model parameters

The comparison between the simulation result from the proposed ferrite bead model and the measurement result of a vendor produced sample SMT ferrite bead is shown in Fig 6. To show the low frequency band less than 100MHz in detail, the comparison was made in a log scale. In graphs of magnitude and phase of S-parameter, the proposed model of the ferrite bead has shown excellent agreement with the measured plot. Various samples were tested for verification of the proposed model, and the proposed model was proven to be accurate and reliable.

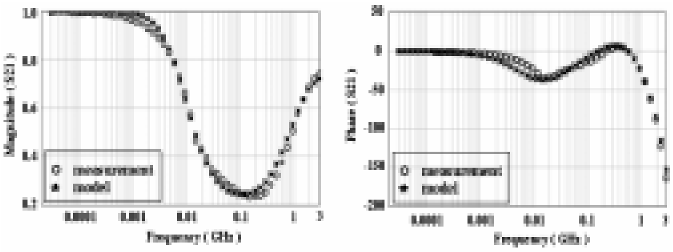


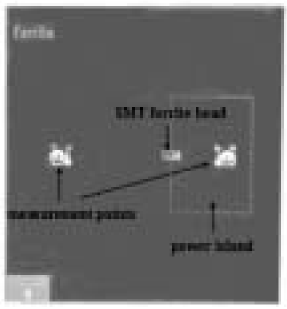
Figure 6. The verification of the proposed model up to 3 GHz. The S-parameters are compared between the simulation result from the proposed model and the measurement result of the test ferrite bead

SMT Ferrite Bead Used in Power Island

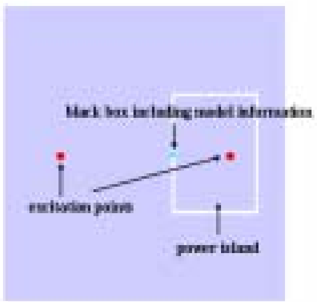
Figure 7. (a) shows device under test (DUT) for measurement in case of SMT ferrite bead used in Power Island. DUT is 4-layer. Second layer and third layer are designed as power plane and ground plane respectively. The size of DUT is 10cm x 10cm. The thickness of dielectric layers are 0.2mm (dielectric between top and power layer and dielectric between ground layer and bottom), and 0.2mm (dielectric between power and ground layers). A half ounce copper layer (17.5μm) is used as ground and power layers. FR-4 is used as dielectric material. Power Island of 4cm x 3cm is made in power plane. As shown in Fig 7, SMA connector was placed in each plane for measurement. SMT ferrite bead is placed on top layer and is connected to each power plane through via. The measurement result is shown in Fig 8. Fig 8 shows that power island is connected to other power plane at DC but is isolated from other power plane at high frequencies.

Figure 7. (b) shows structure drawn with Ansoft Ensemble for Power Island simulation. Structure has the same size as DUT, but structure is composed of 2-layer: top for power plane and bottom for ground plane. In Ensemble 2.5D simulation, via and SMA connectors are not included. S-parameter information of the proposed model is included into black box which connects two power planes.

Fig 8 shows the comparison between measurement and simulation of power island application. All resonance peaks have a good agreement with measurement. The slight difference comes from the structural difference between DUT and simulation structure.



(a)



(b)

Figure 7. The case that SMT ferrite bead is used in power island (a) device under test (DUT) for measurement (b) structure drawn with Ansoft Ensemble for simulation

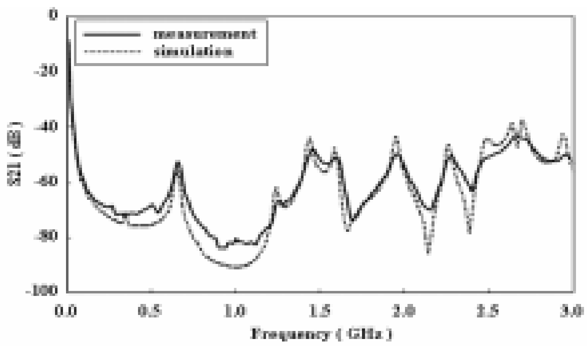
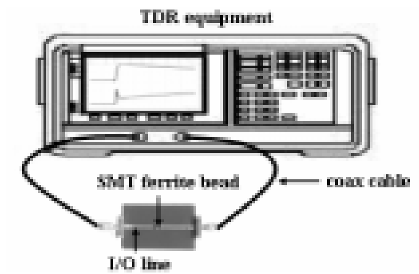


Figure 8. The comparison between measurement result and simulation result

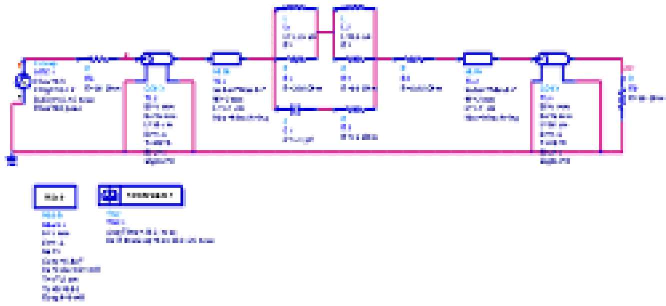
SMT Ferrite Bead Used in I/O Line

Another application is the case that SMT ferrite bead is used in I/O line as a filter. Figure 9. (a) shows DUT for measurement. DUT is 2-layer: top for signal and bottom for ground. The width of signal line is 2mm and the thickness of dielectric is 1mm. A half ounce copper layer (17.5µm) is used as signal line and power plane. FR-4 is used as dielectric material. 2-port time-domain measurement was conducted with Hewlett Packard 54121A and 54120B.

Figure 9. (b) shows schematic for simulation with ADS. Coax cable and SMA connectors used for measurement was considered in simulation. TDR and TDT results from measurement and simulation are shown in Fig 10. Both has an excellent agreement. Also, because TDR equipment having 80ps rising time was used in measurement, the results guarantee up to 3GHz.



(a)



(b)

Figure 9. The case that SMT ferrite bead is embedded into I/O line for filtering (a) measurement setup for I/O line filtering measurement (b) schematic for simulation with ADS: Coax cable and I/O lines used in measurement were considered into schematic

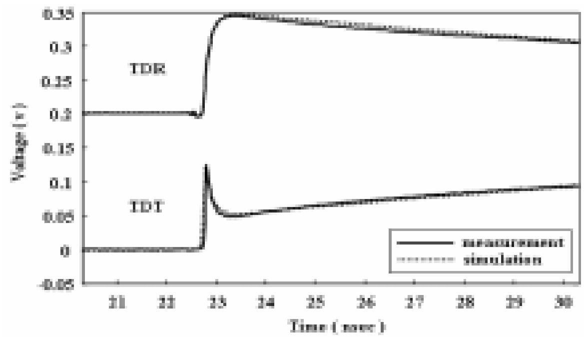


Figure 10. The comparison between measurement result and simulation result

Conclusions

When used for current applications as the EMI reduction or filtering, the ferrite bead is mostly used in a chip type which can be directly mounted to the real circuit, rather than in a bead type. However, previously reported frequency dependent RL model (Figure 2. (b)) is not adequate for the characterization of the SMT ferrite bead. Although the previous model can be applied to the bead type case simulation, the available frequency range is only limited to a few hundreds MHz. There is also another published parallel RLC model (Figure 2. (a)) applicable to the SMT ferrite bead, but the model can be applied only up to a few hundreds MHz. However, the noise frequency in the current high-speed GHz digital systems has risen over GHz range. Accordingly, the precise and reliable model of the SMT ferrite bead over GHz frequency range is heartily needed for the accurate noise simulation on circuit.

In this need, the wide frequency modeling of the SMT ferrite bead has been successfully achieved up to 3 GHz by using the S-parameter measurement. The verification of the proposed model was also made through the comparison between the simulation results using the proposed model and the measured results. The model shows a very good agreement up to 3 GHz with the experiment in terms of magnitude and phase. Good agreement could be achieved because the proposed model considered the frequency dependent characteristic of SMT ferrite bead with lumped R, L, and C.

This model can be easily embedded into circuit and can be used for circuit and PCB level power/ground and I/O line noise simulations. The model actually was embedded into the two typical structures including SMT ferrite bead which were commonly accounted in real field: one for Power Island, and the other for I/O line filtering. When the proposed model was embedded into real board, it also had an excellent agreement with measurements. Also, although the verification was made with a few test chip beads, it is reasonable to think that this model can be applied to all SMT ferrite beads.

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