Vertical Transmission Lines in Multilayer Substrates and Highly-Integrated Filtering Components Based on These Transmission Lines

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1. Introduction

Multilayer substrates such as interposers and printed circuit boards (PCBs) are basic interconnect technologies in modern and next-generation systems in which chip, package and board have been used as constructing elements. Consequently, multilayer substrates have been intensively studied in worldly dispersed electronics packaging research centers in which questions related to how to improve electrical, mechanical, thermal and reliable performances are on the agenda. Moreover, interconnection items affect directly on miniaturization, integration, cost-effectiveness and electrical characteristics of electronics components and, as a result, on promotion of electronics products to the market.

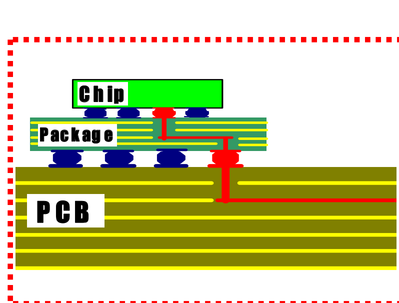


Fig. 1a. A chip-package-board part of a system

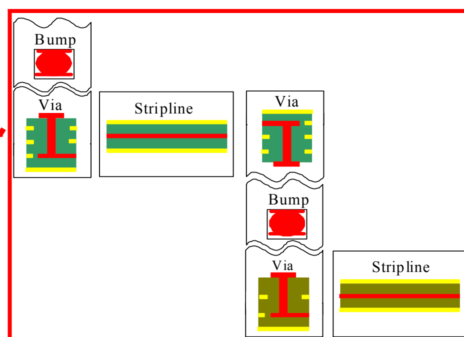


Fig. 1b. A division of an interconnection on bulding blocks

Microwave and millimeter wave areas extremely enhance difficulties in electrical design of interconnected circuits based on multilayer substrate technologies due to impedance

mismatching problems, crosstalk effects, leakage losses, unwanted resonances, dielectric and metal losses, and so on. These issues can be particularly overcome forming interconnections as well wave-guiding structures which can be also used as basic transmission lines of distributed-element passives and actives.

In Fig.1a, an example of a chip-package-board part of a system is shown. Multilayer substrate technologies are realized in the example presented by means of a package and a PCB. An interconnection in the multilayer substrates demonstrated in Fig.1a can be divided into blocks, having their specific characteristics, as shown in Fig.1b. These blocks are represented by planar transmission lines, bumps and vias for the electrical channel shown. One can generalize such building blocks by two groups - horizontal and vertical interconnections - as exhibited in Fig.2.

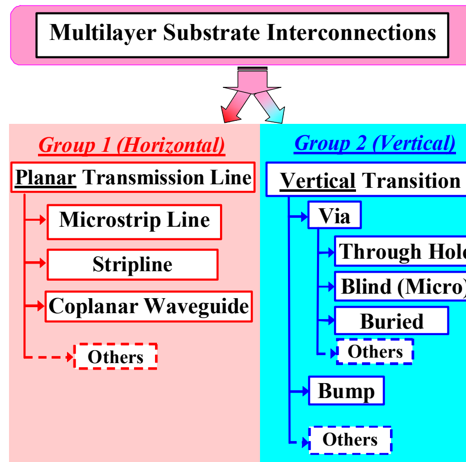


Fig. 2. A generalization of interconnections in a chip-package-board system

To design horizontal interconnections of a high electrical performance, planar transmission lines have been usually used because these structures can provide operation on one (fundamental) mode (for an example, TEM or Quasi-TEM), which has well-defined propagation constant and characteristic impedance, in a wide frequency band. That is why, short and long transmission lines have been used in high-frequency and high-speed systems. Besides that, planar transmission lines in the substrates serve not only as interconnected circuits but also as forming blocks of distributed passive and active components. Consequently, electrical study of planar transmission lines and different functional devices based on these lines has been widely and deeply presented in numerous literatures published (for an example, see comprehensive books (Hoffmann, 1987; Gupta et al., 1996), as for planar transmission lines).

In this chapter, attention will be attracted to the second group of interconnections (see Fig.2) in multilayer substrates, that is, vertical transitions.

Reasons why it will be concentrated on these structures are as following.

Firstly, it can be explained by a significant increase of the vertical transition role in achieving high electrical performance of signal interconnection paths in multilayer

substrates at microwaves and millimeter waves and a contribution of the vertical transitions to impedance mismatching, crosstalk, energy leakage, and other problems which can be excited due to these structures that can finally lead to the fault of the systems, electromagnetic interference (EMI), and other difficulties.
Secondly, it is attractive to use vertical transitions as forming elements of passives and actives (as for an example, short- or open-circuited stubs for filters) and in such way to reduce considerably their dimensions due to:
1) Three-dimensional (3-D) design;
2) Providing an approach to move a functional area for a component to a vertical transition region (see Fig.3).

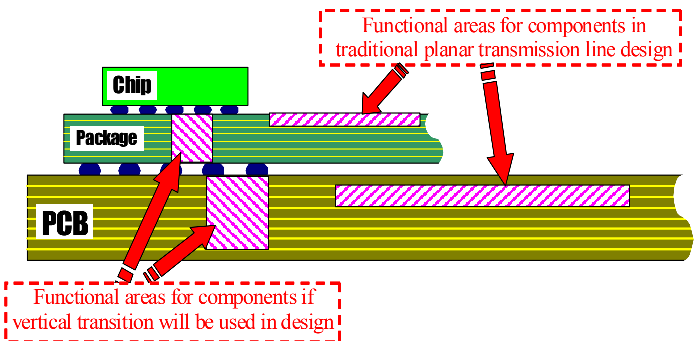


Fig. 3. Approach for miniaturization of a chip-package-board system by means of the use of vertical transitions as forming blocks of a component

2. Shield Via as Vertical Transmission Lines for Multilayer Substrates

Consider vias, as representative structures of vertical transitions, which serve usually to connect planar transmission lines disposed at different conductor layers of multilayer substrates. At microwave and millimeter wave bands, structures similar to a single signal via have poor-defined wave guiding properties and, as a result, they have increasing leakage losses with the growth of the frequency. That is why at these frequencies, propagation constant and characteristic impedance cannot be defined using traditional inductance and capacitance.
As an illustrative example, in Fig.4, the peak of the *E*-field at 10 GHz calculated by a three-dimensional full-wave technique (Weiland, 1996) in a horizontal cross-section between conductor planes of a multilayer substrate comprising the single signal via is shown. As one can see, if the single signal via is placed in the multilayer substrate, then it becomes an effective source of the parallel plate mode excitation. It acts like an antenna exciting parallel plate modes between conductor planes. As a result, such via structure leads to a dramatic reduction of the electrical performance of a whole interconnection due to in-substrate parallel plate-mode resonances and, as their consequence, signal integrity, power integrity and EMI problems. In Fig.5, an impact of the parallel plate-mode resonances on the electrical characteristics of the via is shown by means of the insertion loss. As one can see, the electrical performance of the via dramatically degrades at higher frequencies (in present example, starting from about 2GHz).

Electrical characteristics of vertical transitions can be improved by progressing from through-hole (see Fig.6a) to blind, counter-bored and buried via technologies explained respectively in Figs.6b, 6c and 6d. In these cases, stub effect (Laermans et al., 2001; Kushta et al., 2003) can be removed providing an improvement of signal transmission channel parameters, and the signal via conductor length can be shortened providing a reduction of coupling and radiating areas.
However, in spite of such advancements problems emphasized above remain at microwaves and millimeter waves.

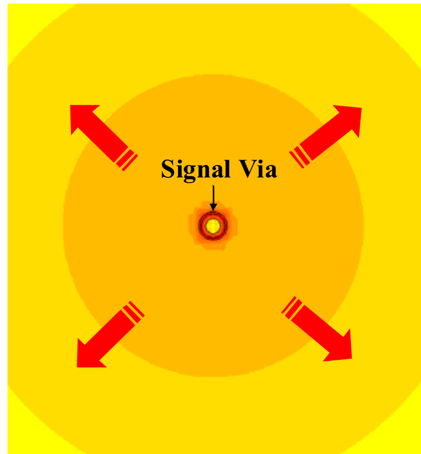


Fig. 4. Simulated peak of the *E*-field taken at 10GHz in a cross-section of a multilayer substrate comprising a single signal via

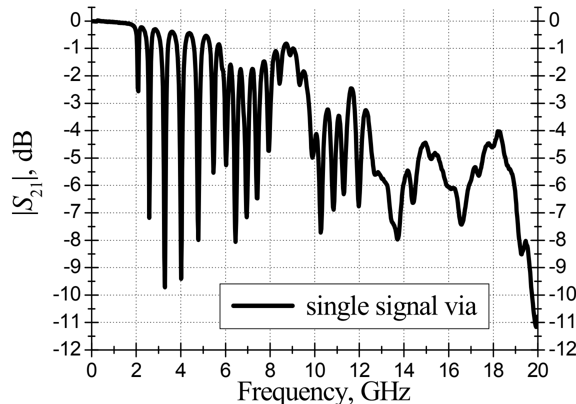


Fig.5. Experimental data for the insertion loss of the single signal via in the multilayer substrate

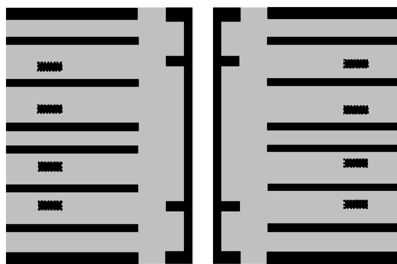


Fig. 6a. Cross-sectional view of through-hole via

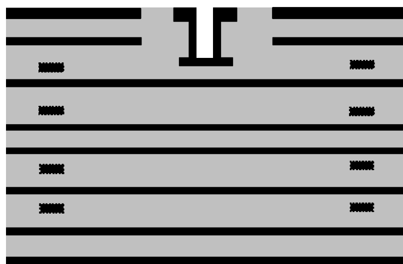


Fig. 6b. Cross-sectional view of blind via

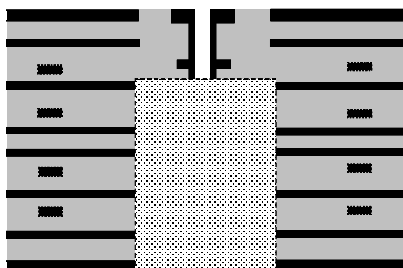


Fig. 6c. Cross-sectional view of counter-bored via

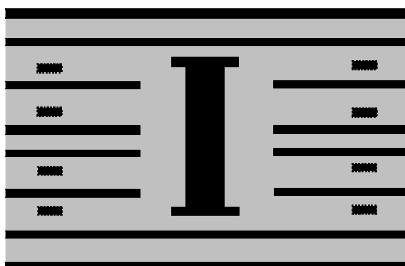


Fig. 6d. Cross-sectional view of buried via

Thus, it comes to be clear that vertical transitions including via structures become an important element in design of high-frequency and high-performance interconnections and components grounded on multilayer substrate technologies.
A solution proposed to provide a high-performance vertical transition in a multilayer substrate is based on forming a shield via as a result of the conjoint use of signal and ground vias. In this case, a specific coaxial waveguide can be formed in the vertical direction of the multilayer substrate (Pillai, 1997; Tarvainen, 2000; Kushta et al. 2002).
Following distinctive examples show advanced characteristics for the shield via compared with the single signal via case. In Fig.7, simulated peak of the *E*-field for the shield via obtained in the same way as for Fig.4 is presented for the identical dimensions of the substrate. As one can see, electromagnetic energy propagating through the shield via is disposed between signal and ground vias. This effect leads to a considerable improvement of the electrical performance for signaling as shown in Fig.8 by means of measured insertion losses (photo of the shield via experimental pattern is in Fig.9). In Fig.8 electrical characteristics of the single via are also given for comparison.
It is well known, to estimate leakage losses in a wide frequency band, *S*-parameters can be used and as for example by means of such equation:

$$Leakage\ Loss,\% = (1-|S_{11}|^2-|S_{21}|^2)\cdot 100\ , \tag{1}$$

where $|S_{11}|$ is the return loss and $|S_{21}|$ is the insertion loss.
In Fig.10, simulated leakage losses for single signal via and shield via with the same parameters as for Figs.4 and 7 are presented. As one can see, the application of the shield via suppresses leakage losses in considered frequency band. It also means that EMI problems can be considerably reduced by the use of such vias in electronics design (Kushta et al., 2004; Kushta & Narita, 2004).

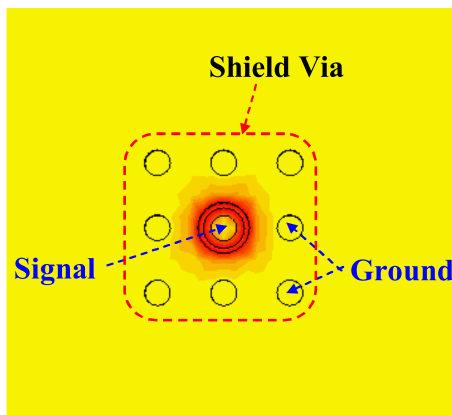


Fig. 7. Simulated peak of E-field taken at 10GHz in the cross-section of the multilayer substrate comprising a shield via

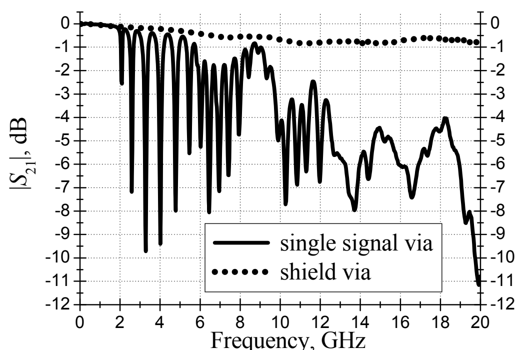


Fig. 8. Experimental data for the insertion loss of both the shield via and the single signal via in the multilayer substrate

Consider leakage effect on the electrical performance of both single and shield via structures in which a digital signal is propagating. In Fig.11, the pulse transmitted through such via structures is shown. As one can see in this figure, signal transmitted through the single signal via has not only higher insertion loss but also higher deformation of the pulse shape that is one of the most important issues in high-speed signaling because, in this case, it is necessary to apply additional techniques like pre-emphasis.

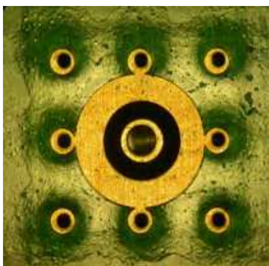


Fig. 9. Photo of the shield via formed by signal and ground vias conjointly

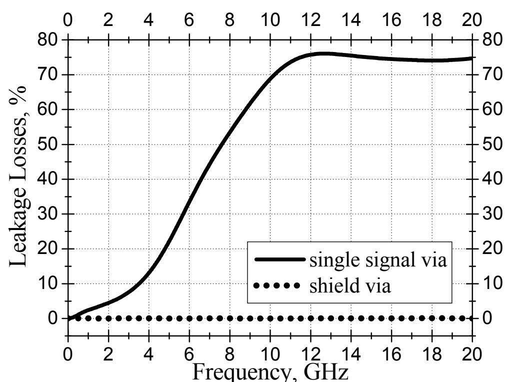


Fig. 10. Simulated leakage losses for via structures calculated according to Eq.1

On the other hand, forming the shield via in the multilayer substrate gives a possibility for a considerable improvement of the electrical performance of the vertical transitions. As follows from Fig.11, the shield via provides significantly lower loss, if it is compared with single signal via case. Moreover, the pulse shape (especially, the width for the signal transmitted) is considerably better for the shield via.

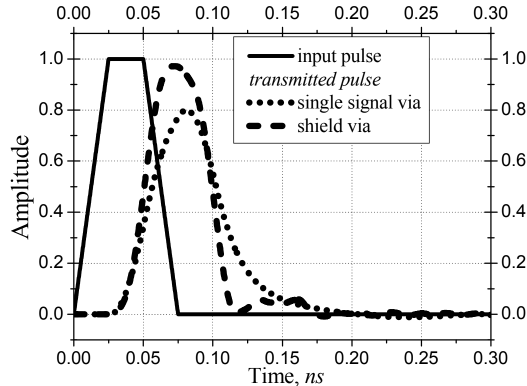


Fig. 11. Signal propagation in single signal via and shield via (transmission)

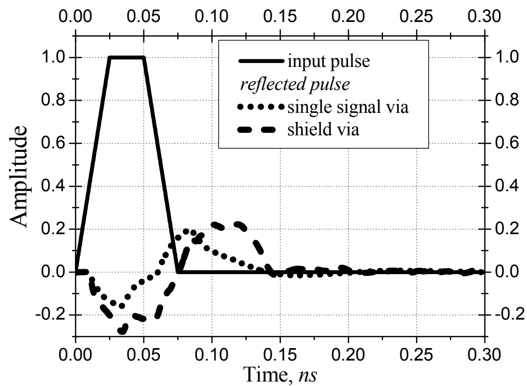


Fig. 12. Signal propagation in single signal via and shield via (reflection)

However, as follows from Fig.12, the amplitude of the reflected pulse is large enough for both via structures. That is why, providing characteristic impedance controlling in a wide frequency band is another important issue to implement the shield vias in real substrates and to achieve their electrical performance similar to that as in planar transmission lines. Therefore, an appropriate physical model showing mechanisms affecting on the electrical characteristics of such type of vertical transitions has to be defined.

Consider the shield via as in Figs.13a and 13b. This structure is formed in an 8-conductor layer substrate. Corrugated coaxial waveguide model (Kushta et al., 2002; Kushta et al., 2004) is proposed to describe physical processes in the shield via. In this model, ground vias are replaced by continuous and smooth conductive surface which acts as an outer

conductive boundary and the signal via serves as an inner conductive boundary of such coaxial waveguide. Also in the model, conductive plates from conductive layers of the multilayer substrate disposed between inner and outer conductive boundaries are considered as specific corrugations of the outer conductive boundary. The corrugated coaxial waveguide model for the shield via shown in Figs. 13a and 13b is presented in Figs.14a and 14b.

In consequence, the outer conductive boundary of such corrugated coaxial waveguide model can be characterized as a surface for which the surface impedance can be approximately defined as:

$$Z_s \approx 120\pi \cdot i \cdot \sqrt{\frac{1}{\varepsilon}} \cdot \tan\left(\frac{2\pi \cdot f}{c} d \cdot \sqrt{\varepsilon}\right) \quad (2)$$

where d is the corrugation depth defined as $d = (D_r - d_{cle,r} - d_{gr})/2$, f is the frequency and c is the velocity of light in free space. Note that Eq.(2) is valid under following conditions:

$$H_{i,j} << \lambda , \quad (3)$$

where λ is the shortest wavelength in the isolation material of the multilayer substrate in considered frequency range; $H_{i,j}$ is the distance between i-th and j-th conductor planes; $j = i + 1$.

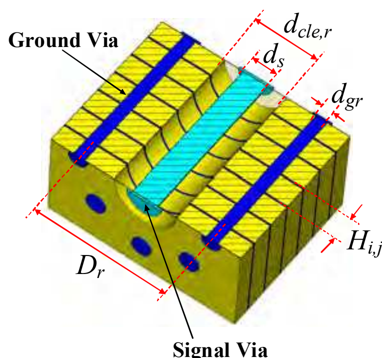


Fig. 13a. Cross-sectional view of shield via

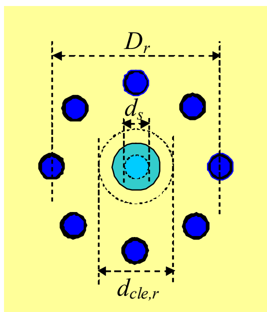


Fig. 13b. Top and bottom views of shield via

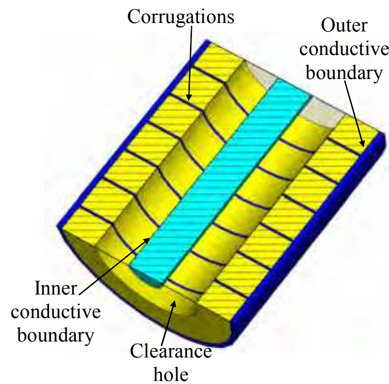


Fig. 14a. Cross-sectional view of corrugated coaxial waveguide model

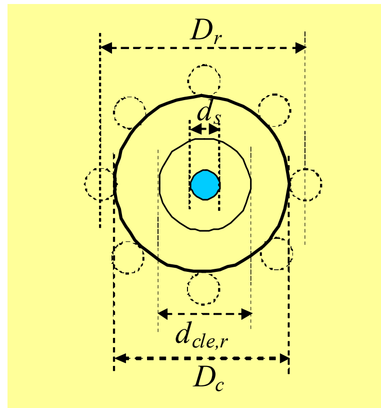


Fig. 14b. Top and bottom views of corrugated coaxial waveguide model

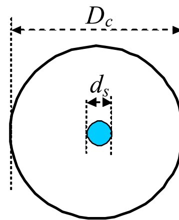
Eq.2 gives a simplified physical mechanism which can explain signal propagation in the shield via. In particular, if corrugations in the coaxial waveguide model are large enough, then the surface impedance of the outer conductive boundary is dependent on the frequency. It means that broadband matching of the shield via with other interconnected circuits having usually approximately constant (or weakly frequency-dependent) characteristic impedance is a difficult problem.

Thus, to provide a broadband high-performance operation of the shield via it is necessary to decrease such the corrugations as much as possible. If this condition will be satisfied, then an approximate equation for the surface impedance can be written as follows:

$$Z_s \approx 0 \,. \tag{4}$$

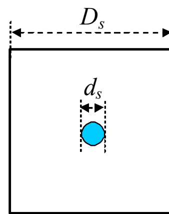
The surface impedance defined according to Eq.4 corresponds to the smooth conductive boundary and, in this case, signal propagation in the shield via can be considered as in a corresponding coaxial waveguide.

As a validation of this coaxial waveguide model, consider two types of shield vias in the multilayer substrate. The first type comprises the outer conductive boundary of a round arrangement of ground vias. The second type is consisted of ground vias with a square arrangement. From coaxial transmission line theory (Wheeler, 1979), there are known analytical formulas for the characteristic impedance of round and square coaxial waveguides. In Figs.15a and 15b, expressions for these coaxial waveguides are presented under the drawing of the corresponding structure by Equations (5) and (6), respectively.



$$Z_r \approx 60 \cdot \sqrt{\frac{\mu}{\varepsilon}} \cdot \ln\left(\frac{D_c}{d_s}\right) \tag{5}$$

Fig. 15a. Cross-section view of round coaxial waveguide and its characteristic impedance



$$Z_{sq} \approx 60 \cdot \sqrt{\frac{\mu}{\varepsilon}} \cdot \ln\left(\frac{1.0787 \cdot D_s}{d_s}\right) \tag{6}$$

Fig. 15b. Cross-section view of square coaxial waveguide and its characteristic impedance

As follows from these equations, which are defined for the coaxial transmission lines with continuous and smooth inner and outer conductive boundaries, the characteristic impedance will have the same magnitude for round and square cases if the diameter of outer boundary of the round transmission line and the side of the square transmission line will satisfy the following identity:

$$D_c \approx 1.0787 \cdot D_s \,. \tag{7}$$

It should be noted that Eq.7 is valid if other parameters of round and square coaxial transmission lines such as the diameter of the inner conductor and constitutive parameters (such as relative permittivity, ε and relative permeability, μ) of the isolating material are the same.
So, first of all, a validation of the coaxial waveguide model will be provided in such manner. If this model is appropriate for the shield via, then identity (7) will be satisfied for shield

vias with round and square arrangements of ground vias around the signal via. To verify this feature, round and square shield vias with $D_c = 3.2mm$ and $D_s = 2.967mm$ have been considered. Cross-sectional views of these via structures are presented in Figs.16a and 16b.

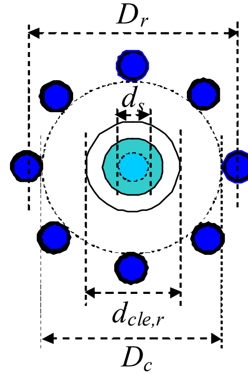


Fig. 16a. Shield via with round arrangement of ground vias

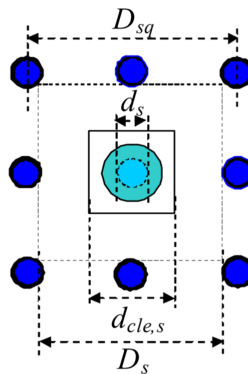


Fig. 16b. Shield via with square arrangement of ground vias

Other dimensions of aforementioned shield via structures are as following (see Fig.17): $d_{pad} = 0.95mm$, $d_{cle,r} = 1.65mm$, $d_{cle,s} = 1.53mm$ and $d_s = 0.65mm$. The shield via structures have been embedded in the substrate which consists of eight copper planar conductor layers isolated by FR-4 material with the relative permittivity of $\varepsilon = 4.17$ and loss tangent of $\tan\delta = 0.023$ as assumed in simulations. Spaces between planar conductor layers as shown in Fig.17 are: $H_1 = 0.2mm$, $H_2 = 0.385mm$ and $H_3 = 0.24mm$; the thickness of conductor planes embedded in the substrate is $t = 0.035mm$; the thickness of top and bottom conductor planes is $t_t = t_b = 0.055mm$.

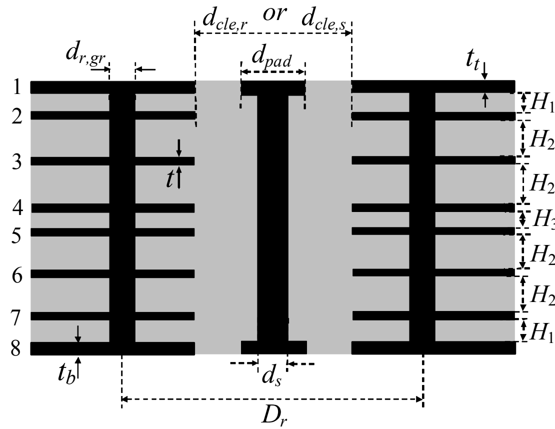


Fig. 17. Vertical cross-section view of shield via in 8-conductor-layer substrate

In Figs.18a and 18b, magnitudes of simulated *S*-parameters for two shield vias with round ($D_c = 3.2mm$) and square ($D_s = 2.967mm$) arrangements of the ground vias in the 8-conductor-layer substrate are presented. As follows from simulated *S*-parameter data shown in these figures, structures with round and square arrangements of ground vias having transverse dimensions defined according to Eq.7 demonstrate practically the same electrical performance in considered frequency band. It means also that the characteristic impedance in structures presented is the same one and, as a result, aforementioned shield vias are practically equivalent.

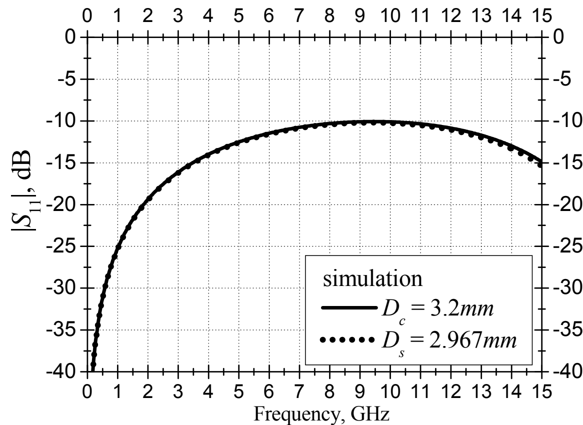


Fig. 18a. Simulated return losses for two shield vias with round and square arrangements of ground vias

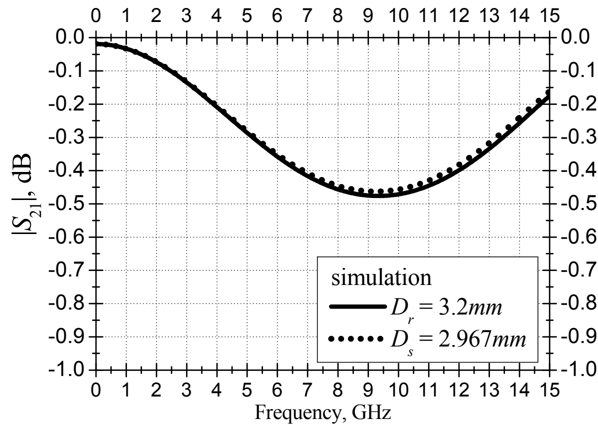


Fig. 18b. Simulated insertion losses for two shield vias with round and square arrangements of ground vias

Simulated results presented in Fig. 18a and 18b serve a proof of a simplified mechanism for signal propagations in the shield via formed by signal and ground vias conjointly as in the corresponding coaxial waveguide with smooth and continuous conductive boundaries. This consideration gives a way to define the characteristic impedance of the shield via in the multilayer substrate that is important to design well-matched interconnected circuits using multilayer substrate technologies.

Note that the corrugation depth for considered round and square coaxial waveguides is the same due to the appropriate choice of the clearance hole form and dimensions. In these cases, the round shield via has the round clearance hole, while the square shield via has the square clearance hole. Also, dimensions of the clearance holes are defined according to Eq.7.

Above-mentioned data have been obtained by three-dimensional full-wave simulations which usually give an adequate description of electromagnetic processes in a test structure. However, each theoretical model is idealized one, which does not include the frequency dependency of board isolating material, roughness and tolerances of shapes of conductive surfaces, and so on. That is why the experimental study of test structures serves not only as an evidence of their theoretical models but also gives a real wide-frequency band behavior of the structures studied.

In following Fig.19a and 19b, measured magnitudes of *S*-parameters for the shield vias whose simulated data are respectively presented in Figs. 18a and 18b are shown and demonstrate the electrical behavior similar to their simulation models. As follows from theoretical and experimental data, characterization of the shield vias in the multilayer substrate as specific coaxial waveguides is a vital and useful approach to design high-frequency and high-speed electrical vertical transitions.

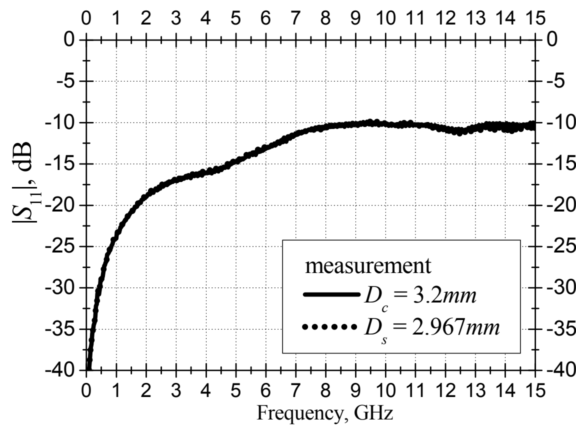


Fig. 19a. Measured return losses for two vertical transitions with round and square arrangements of ground vias

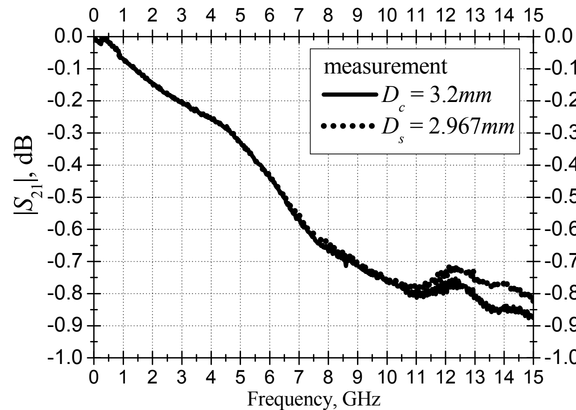


Fig. 19b. Measured insertion losses for two equivalent vertical transitions with round and square arrangements of ground vias

As another verification of the corrugated coaxial waveguide model and also as recommended design steps based on the application of this model, an effect of the distance between signal and ground vias on the electrical performance of the shield via is presented. Two square arrangements of ground vias having $D_s = 2.04mm$ and $D_s = 2.967mm$ (other parameters are the same as in aforementioned cases, except that the clearance hole has the side $d_{cle,s} = 1.16mm$) have been considered here that approximately corresponds characteristic impedances calculated according to Eq.6 as $Z_{sq} \approx 36Ohms$ and $Z_{sq} \approx 47Ohms$. Measurement data for these shield vias are shown in Figs.20a and 20b. Note that top and bottom parts of the shield vias considered were connected to 50*Ohms* coaxial cables. As follows from figures presented the highest electrical performance in all frequency band (up to 15*GHz*) is achieved

for the shield via with $D_s = 2.967mm$. This shield via is better matched to $50Ohm$ cables that is an indirect validation of the coaxial waveguide model. However this is only one important point of the physical model presented because corrugations are another its key point.
Thus, as next, the clearance hole effect on the electrical performance of the shield via is shown that is associated with the corrugation depth in the physical model presented. Measurement data for two shield vias with different dimensions of the clearance hole are demonstrated in Fig.21a and 21b.
The shield vias have the same dimensions and are embedded in the same 8-conductor-layer substrate, as in above-mentioned examples. In considered shield vias, clearance holes have the square form with the side of $d_{cle,s} = 1.53mm$ and $1.16mm$ and for both shield vias $D_s = 2.967mm$. As one can see increasing the clearance hole dimensions leads to a considerable improvement of the electrical performance of the shield via in the wide frequency band.

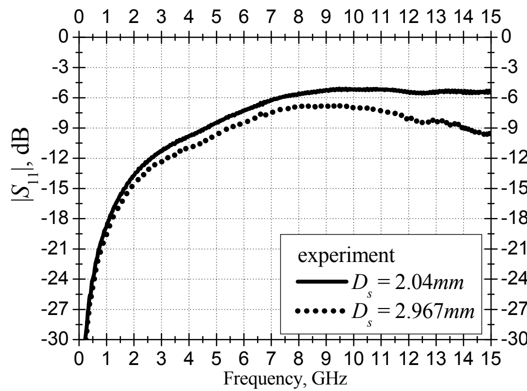


Fig. 20a. Measured return losses for shield vias with square arrangements of ground vias (effect of distance between signal and ground vias)

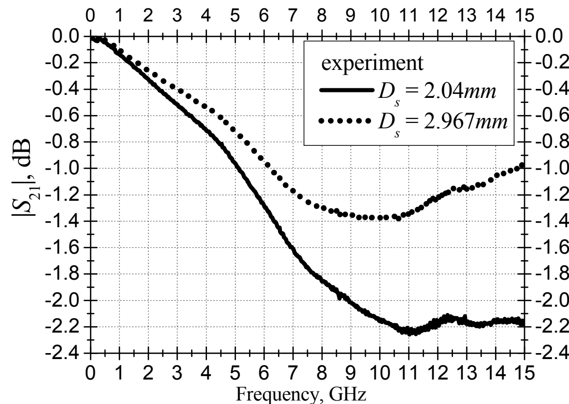


Fig. 20b. Measured insertion losses for shield vias with square arrangements of ground vias (effect of distance between signal and ground vias)

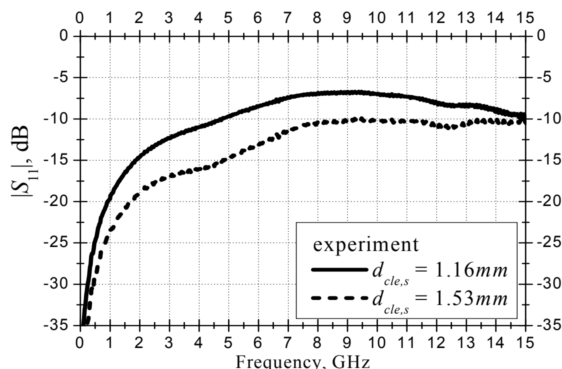


Fig. 21a. Measured return losses for shield vias with square arrangements of ground vias (clearance hole effect)

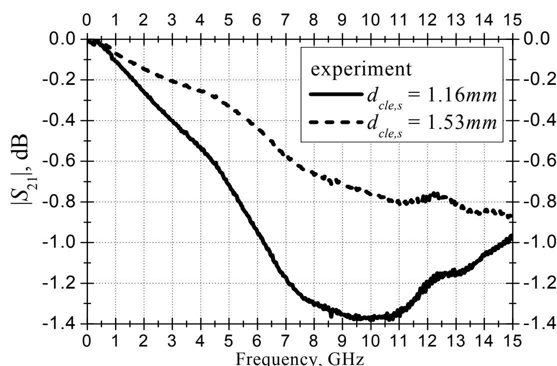


Fig. 21b. Measured insertion losses for shield vias with square arrangements of ground vias (clearance hole effect)

As a result of these considerations, two main points can be categorized as a basis which can provide a high-performance vertical transition in the form of the shield via. They are obtained as following from the corrugated coaxial waveguide model given here.

1) Signal via transversal dimensions and distance between signal and ground vias in a shield via have to be chosen in such way to provide a required characteristic impedance calculated according to an appropriate coaxial transmission line corresponding to the shield via.

2) A clearance hole has to provide minimal corrugations of the ground plates in the coaxial wave guiding channel.

As one can see, in presented examples, cases when signal is propagating from the top to the bottom of the multilayer substrate are considered. However in real applications, the shield via has to be connected to a planar transmission line disposed at a conductive layer of a multilayer substrate. And this connection can not be decided in a simple way at microwaves and millimeter waves and, that is why, it becomes an important issue. In following paragraph, a technique to provide a high-performance transition from the shield via to the planar transmission line will be shown.

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