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SHORT COMMUNICATION

High Performance Interconnection Technology in Avionics

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ABSTRACT

Avionics sub-systems continue to get smaller and more functional, driving the total circuit package itself to become denser, causing the printed wiring board (PWB) to evolve new laminates to meet these needs. There is a continuous scope for improvement to match the requirement of wireability demand from high density and high speed integrated circuits. Development of control processing units and rapid expansion of memory device capabilities were realised by the development of large-scale integrated circuits and other electronic devices with higher integration and with new functionalities. Enormous efforts have been put on the development of the system-on-chip (SOC), where a single semiconductor chip constituting complete system is bonded on substrate. These innovations in packaging technology made a big impact on laminates used in printed circuit boards. Aircraft systems are expected to withstand disturbances due to unexpected threats. Under such situations, passengers' safety, emergency landing and timely information to pilot become of paramount importance, hence, new innovative laminate systems are being developed. Various aspects of laminates and the current developments that are taking place are facilitating scientists and engineers in selecting appropriate laminate systems, have been discussed.

Keywords: Avionics, integrated circuits, large-scale integrated circuits, packaging technology, system-on-chip, laminates systems, interconnection technology

1. INTRODUCTION

With continuous innovation and advancement in electronics, more and more aerospace systems, from aero-engine to passenger entertainment, have advanced electronic circuitry as an integral part of their functioning and forms large portion of non-recurring cost of the airplane systems[2]. Mobile communication services are provided for the passengers. While servicing the aircraft, technicians are provided with special goggles which can project three-dimensional diagrams, which facilitate to use both hands repair, thereby dispensing off the conventional manual. Aerospace systems require high performance interconnectivity with excellent electrical and proven performance.

From the perspective of defence, air force of a country has a major role to play in warfare strategy. With the introduction of various types of missiles, active aperture phase array radar and airborne surveillance systems, the need for high performance has increased. Reliability of the system needs to be addressed, right from the beginning by the selection of appropriate process components and laminates.

Success of an industry depends on its capability to discover, innovate, and incorporate technical knowledge. Rapid globalisation of world markets and economies alter the international business relationships, competition, and other issues, thereby widening the challenges for interconnection industry for time to market and cost efficiency[2]. Prosperity of such an organisation depends on new products brought out by the integration of engineering disciplines. Development of control processing units and rapid expansion of memory device capabilities, realised by the development of large-scale integrated circuits (LSI) and other electronic devices with higher integration and with new functionalities. Enormous efforts have been made for the development of system-on-chip (SOC), where a single semiconductor chip constituting a complete system is bonded on substrate. These changes in packaging technology made a big impact on the laminates used in printed circuit boards(PCBs)[5].

The global market for the PCBs (which was around $ 52.6 billion during 2007 with major contributions from Japan, china and Taiwan) are forecasted to be over $ 76 billion in 2012. Production in India is around $ 0.34 billion[13]. As can be seen, PCB industry is globally well established and is focusing towards products having large demand such as consumer, communication, computing, etc. PCB manufacturing is highly process-oriented and uses expertise from different branches of science and engineering. The industry uses many proprietary materials which have their optimised parameters to achieve production efficiency and profits. With the mandatory requirement of global standards, processes and laminate systems need to be improved continuously. This necessitates initiation of research activities in the area of airborne laminate system to match the ever increasing interconnection densities. This forms an important expertise towards building core competency and concurrent engineering, which are essential for making a product successful.

Avionics systems are a complex mix of computers, sensors, radar, communication, navigation, actuators and display units that are integrated and majority of these are located in the

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cockpit of the aircraft. Avionics subsystems continue to get smaller and more functional, driving the total circuit package itself to become denser, causing the PWBs to evolve new laminates to meet these needs. There is continuous scope for improvement to match the requirement of wireability demand from high density ICs (BGA, FPGA, etc.) interconnection.

2. AREAS OF RESEARCH AND INNOVATION

To maintain market leadership on a global scale, the industries are focusing towards the performance of the electronic systems. To achieve this, research and innovation are focused in the following areas.

2.1 Semiconductor Technology

Semiconductor technology has grown from the humble transistor to design complex processor, and further development in monolithic microwave integrated circuits (MMICs), optical, nanotechnology, making industries possessing their technology to be the leader. In fact, technology capability of a nation can be accessed by its expertise in this field.

Printed circuit board (PCB) industry has a close link with the ICs industry. PCB industry has to meet the challenges posed by the new developments in ICs industry. Ultimately, unless PCBs are able to deliver performance of the ICs and chips to the outside world, it will lose its share in the market. The semiconductor industry was around 90 nm node last year (2010) and heading towards 40 nm[1]. The dimension refers to the smallest feature size of the transistors on the integrated circuits (ICs). The feature size is a defining aspect of advanced ICs technology, because smaller features result in better ICs performance and lower costs[3]. Further it was observed that the chip size of semiconductor stays relatively constant, while the number of I/Os rapidly increases: decreasing the available space for interconnection[6]. This can act as guidelines for future PCB laminate systems.

With a larger integration of LSI, the number of gate circuits increases, leading to a larger I/O pin count. The empirical rule of Rentwell describes the relationship between the number of gates and the number of I/O pins as,

$$N = aG^b \qquad (1)$$

where G is the number of gates within an LSI chip, N is the I/O pin count, and a, b are constants[5]. Rapid widespread growth of digital technologies enabled affordable Intelligence, control, and integration to penetrate many commercial, aviation, automotive, medical devices, desktop computing, etc[6].

2.2 Fabrication Process

Innovation and developing a new process have been the hallmark for the success of PCB industry, starting from the platted through hole (PTH) technique to todays sequential build-up process unit (SBU). A multilayer printed wiring board (PWB) built by an SBU process, referred to as built-up multilayer (BUM) characterises the manufacturing process. The SBU aims to achieve line definition to match the chip technology and its I/O terminal density[5].

Electronic products consist of ICs, resistors, capacitors and other discrete components, mounted and interconnected on a PWB. The advantages of PCBs include predictability of electrical performance, repeatability of manufacture, reliability and ability for mass soldering and to carry a thermal conducting path and meeting increased speed, signal integrity, and EMI/EMC. These modules are further connected together to complete an end product for electronic system. The hierarchy of packaging and interconnection levels is illustrated in Fig. 1.

The major task of packaging and interconnection technology is to physically expand the signals to practically usable size down to the next level of the packaging hierarchy without deteriorating the original performance of LSI at its output terminals. Printed wiring board plays an important role in achieving this.

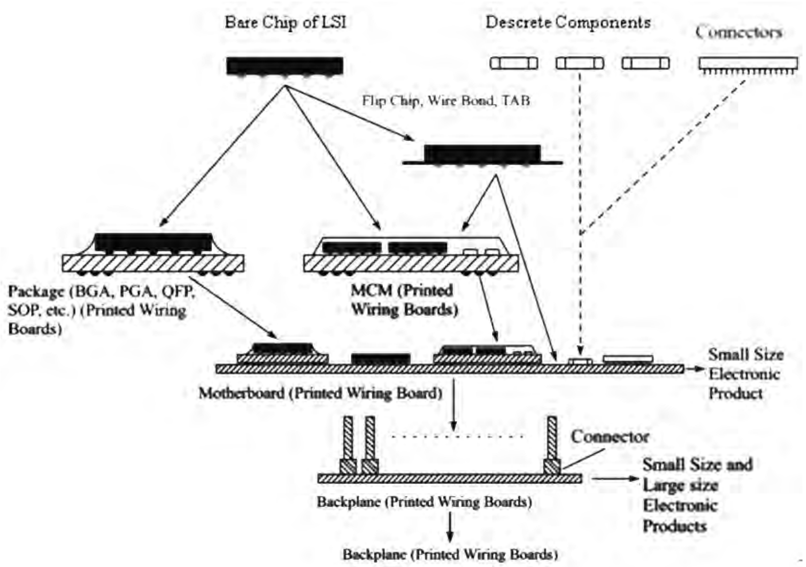


Figure 1. Packaging hierarchy of electronic products.

2.3 Laminate System for Airborne Applications

Laminates play a key role in achieving the required product quality and reliability. The challenge for the industry is on knowledge fusion from cross-disciplined fields which include physics, chemistry, electrical engineering, computer engineering, mechanical engineering, material science, and chemical engineering, resulting in innovative products. New laminates are being developed to meet new wireability requirement and environmental issues. High glass transition temperature (*Tg*) laminate such as improved FR-4 is an example. High frequency laminate, laminate with low warp, and laminate suited for lead-free solder are few examples. Even though new techniques is being developed (such as SBU) to achieve higher line definition, laminate processing is preferred as this is cost-effective, well established, and can be globally outsourced.

The laminate base material is made up of three components, the resin system, the reinforcement, and the conductive foil. Though the base material appears deceptively simple, the variants in each of these components and many possible combinations in these components make the choice of base materials complex[5,7]. With the huge demand from commercial entertainment sector, new products focus on developing and meeting such requirements. In view of this, new programmes are initiated to develop laminates for defence including application in aerospace industry. Laminate should withstand operational and storage temperature and also withstand stress due to soldering operation. For airborne applications, organic and inorganic substrates are used. Organic substrates use layers of woven or non-woven glass cloth for reinforcing impregnated with epoxy resin, polyimide, cyanate ester, BT resin, etc. Non organic substrate consists mainly of ceramic and metallic materials such as aluminum, soft iron and copper- invar-copper, which can meet the heat-dissipation requirement.

Laminates are commonly classified by two schemes-National Electrical Manufactures Association (NEMA) grades and IPC-4101 specifications[10,11].

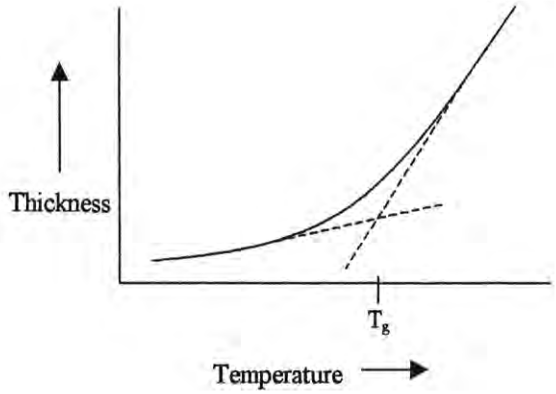


Figure 2. Glass transition temperature by thermo-mechanical analysis.

While selecting laminates, their *Tg*, is an important criterion. At *Tg,* physical changes take place due to weakening of molecular bonds within the material. Above which, the rigid or glass state of the laminates change to a deformable or softened state, having implications on thermal expansion and degree of cure. The rate at which the material expands is much lower below the *Tg* than above influencing the reliability of the finished circuit, shown in Fig. 2.

The lower expansion of laminates result in greater reliability as less stress is applied to platted through holes and pads. Apart from this, *Tg* affects the hardness of the laminate which influences drilling and stack heights. Further, lower copper peel strength values and shorter times to delamination can also be correlated with higher *Tg* values. In view of these, *Tg* is just one important property that must be given due consideration when choosing a resin system. Balancing this property with others is crucial in achieving good manufacturability and reliability[11]. Based on the end use of the finished PCB in the aerospace application, one of the main criteria for selection of the laminates is its *Tg*. Table 1 gives the details of reinforcement type, resin system, and its *Tg* for important laminates.

Table 1. Base material summary[10]

Specification sheet	Reinforcement type	Resin system	ID reference	*Tg* range
23	Woven E-glass fabric	Fabric epoxy, hot strength retention, flame-resistant	NEMA FR-5, MIL-S-13949/ 05—GH	135–175 °C
24	Woven E-glass fabric	Fabric majority epoxy modified or unmodified, flame-resistant	NEMA FR-4, MIL-S-13949/04—GF/GFG	150–200 °C
30	Woven E-glass	Triazine and/or bismaleimide-modified epoxy, flame-resistant	MIL-S-13949/26—GFT	170–220 °C
42	Woven E-glass	Polyimide	Polyimide MIL-S-13949/10—GI/GIJ	200–250 °C
71	Woven E-glass	Cyanate ester	MIL-S-13949/29—GC	>230 °C
82	Woven E-glass	Epoxy resin (catalysed for additive process), flame-resistant	NEMA FR-4	110 °C

3. PROPERTIES OF BASE MATERIALS FOR AEROSPACE APPLICATIONS

Some of the properties of base materials that are used for various aerospace applications and having wider implications in terms of manufacturing, assembly, and end user which are considered during selection of laminates include

Important properties of laminates are

- Coefficient of thermal expansion
- Maximum continuous operating temperature
- Electrical properties
- Mechanical strength
- Flame resistance
- Overall thickness tolerance
- Flexural strength
- Reinforcing sheet material
- Glass transition temperature
- Resin formula
- Machinability
- Thermal stability

Airborne systems have to withstand severe conditions like operating temperature of 55 °C to 95 °C compared to other category of system like consumer which operates at 0 °C to 60 °C**.** The requirement of low failure rate, of the order of 0.001 per cent, demands the selection of appropriate materials. The PCB base materials form a critical system and have an influence on overall performance. If a decision on selecting an appropriate laminate is not correctly made, it can lead to system failure, execution delay, escalation in cost, and losing business opportunities.

3.1 Testing of Laminates

Inter-process-communication (IPC) has brought out comprehensive testing method manual, IPC-TM-650. These are well established and reliable guidelines for industries. Some of the salient features applicable to aerospace industry are:

(i) *Thermal expansion*: The rates of thermal expansions of the materials are different in *x* and *y* planes and *z* plane due to directionality of reinforcement (*x* and *y* planes refer to along the two surfaces of the laminates and *z* plane is along the cross-section of the laminates), *z* axis coefficient of thermal expansion can cause deformation in the plated through holes and also can cause stress on the copper pads on the surface of the printed circuit, and subsequently appear lifted from the surface upon cooling. *x/y* coefficient of thermal expansion is of particular importance when chip-scale packages (CSPs) and direct chip attach components are used, wherein reliability of the bond will be affected. Appropriate resin system, additives, and fillers are selected to lower the CTE of the material. Typical *z*-axis expansion values ranges from 3.5 to 4.5 (per cent from 50 °C to 260 °C) and x/y CTE value ranges from 10-14 (ppm/°C from -40 °C to 125 °C) [18].

(ii) *Thermo-mechanical analyzer:* Is a specific test procedure used to measure time to delamination i.e. how long a material will resist blistering or delamination at specific temperature. It is measured in terms of minutes and varies from 4 min to > 30 min. The values for different laminate are given in Table 3.

(iii) *Decomposition temperature*: Measures actual physical degradation of the resin system. This test uses thermogravimetric analysis (TGA), which measures the mass of a sample versus temperature and values for laminates are given in Table 3.

(iv) *Arc resistance*: Describes the time the material resists tracking, or forming a conductive path when low-current arc is placed above the surface of a material. Table 3 compares the performance of various material types.

(v) *Copper peel strength*: Is the most popular method used to measure the bond between the conductor and the substrate. It is accepted practice to use 1- 0 z cladding. Typical values vary from 6.1 lb/in to 9.0 lb/in and details are given in Table 3. This has direct implication for deciding fine line width on the board.

(vi) *Measuring and monitoring of peel strength:* Further measuring and monitoring of peel strengths for comparison to its normal values can be used as a process control tool or an inspection criteria or for failure analysis purpose.

(vii) *Flexural strength*: Is a measure of the load that a material withstands without fracturing when supported at the ends and loaded in the centre. In airborne application, system will be subjected to extreme vibration and reliability of

Table 3. Important thermal properties of common base material types[10, 18]

Material	T_g(°C)	Blistering resistance (min.) at 260 °C	Decomposition temperature (°C 5 per cent wt loss)	Arc resistance (s, min)	Peel strength after solder float (lb/in)
FR-4 epoxy	140	8-12	290-310	65	9.0
Filled FR-4 epoxy	155	13	317	124	7.0
High Tg FR-4 epoxy	180	4-30	300-330	65	9.0
BT/epoxy blend	185	30+	334	118	8.9
Low-D_k epoxy blend	210	30+	357	123	7.5
Cyanate ester	250	30+	376	160	8.0
Polyimide	250	30+	389	136	7.5
APPE	170/210	30+	360	…………	6.1

soldering of SMD, BGA and SOC will get affected by the flexural strength. Typical minimum flexural strength lengthwise for commonly used airborne laminates[18] is of the order of 4.23 x107 kg/m^2 and minimum flexural strength cross-wise is of the order of 3.52 x 107 kg/m^2.

(viii) *Resist conductive anodic filament:* Besides causing defects, absorbed moisture affects the ability of a material to resist conductive anodic filament (CAF) formation when a bias is applied to the circuit. As the Aerospace systems have long life span of 20 years, cumulative effect due to moisture absorption need to be taken into account during design. Typical moisture absorption values ranges from 0.1 per cent to 0.35 per cent and methylene chloride[18] resistance values ranges from 0.32 per cent to 0.7 per cent. Some, which influence the selection process are chemical resistance and flammability.

There are a variety of base materials electrical properties which influence the overall performance of the circuit. Accurate values of these properties will help in analysing the circuit and predicting the performance characteristics over the operating frequency, speed, temperature, and environment. Dielectric constant and dissipation factor vary with temperature, humidity, and also resin content. It is also a function of operating frequency.

Table 4 shows dielectric constants and dissipation factors of common airborne laminate materials. Controlled impedance line can be designed by knowing the correct value of the dielectric constant. The dissipation factor helps to estimate the loss at higher frequency.

When high performance limit is to be achieved from the laminate, additional electrical properties that are generally considered include volume resistivity, surface resistivity, and electric strength. These have impact on the overall performance.

Table 4. Dielectric constants and dissipation factors[18]

Material	Dielectric constant		Dissipation factor	
	1 MHz	1 GHz	1 MHz	1 GHz
FR-4 epoxy	4.4	3.9	0.027	0.015
Filled FR-4 epoxy	4.5	3.96	0.023	----
High Tg FR-4 epoxy	4.4	3.9	0.023	0.012
BT/epoxy blend	4.1	3.8	0.013	0.010
Epoxy/PPO	3.9	3.8	0.010	0.011
Low-D_k epoxy blend	3.9	3.8	0.009	0.010
Cyanate ester	3.8	3.5	0.008	0.006
Polyimide	4.3	3.7	0.013	0.007
APPE	3.7	3.4	0.005	0.007

4. MANUFACTURING PROCESS AND LAMINATE SELECTION

PCB manufacturing involves number of specialised processes in the area of chemical, mechanical, photolithography, and electrical testing. Typical process sequence is shown in Fig. 3. Laminate selection involves understanding the reaction/impact of various processes on the properties of the laminates and consequent effects on the finished board performance. Optimisation of the properties needs to be carried out based on a specific aerospace application.

4.1 Industry Standards and Guidelines for Avionics

Initial work in this field was initiated by military organisations that developed hardware and software using specialised defence-oriented standards such as 2167A, 498 and 882. However, industries prefer adopting DO-178B and DO-254. RTCA/DO-178B is a standard developed by industry as more and more software and embedded codes were used in various applications like safety-critical and avionics applications. The formal standard software considerations in airborne and equipment certification known in the industry as DO-178/ED-12B is used as the means by which government certification authorities such as the FAA1 and EASA2 determine that aircraft and engines containing software as part of their operational capability can be granted the necessary airworthiness certification needed for operation in civil airspace. The DO-254 body offers design guidelines and certifications for hardware engineering that are being

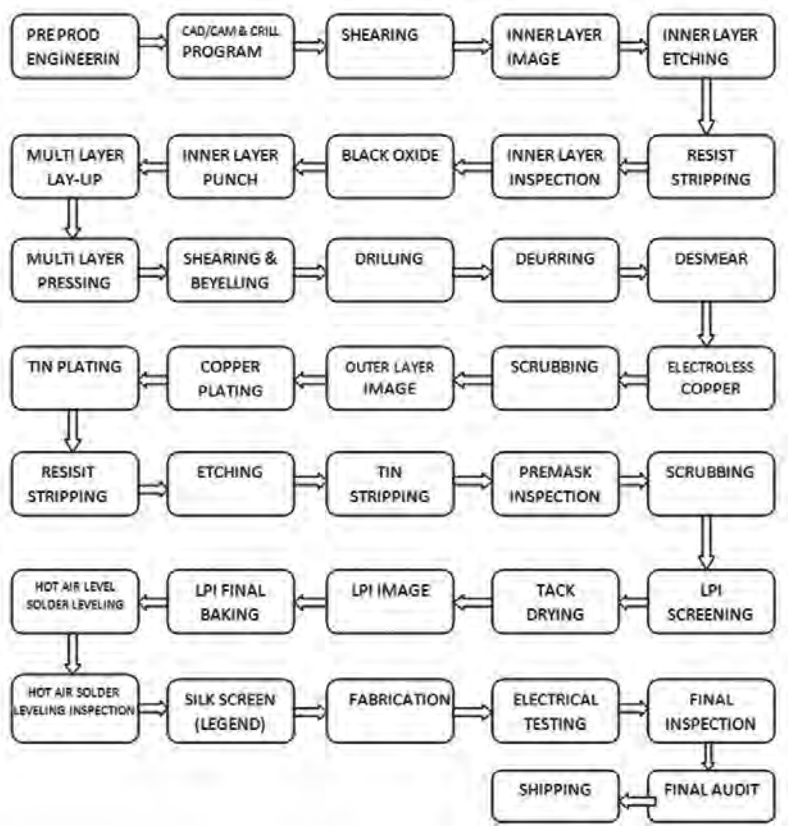


Figure 3. Typical flow chart for multilayer circuit boards.

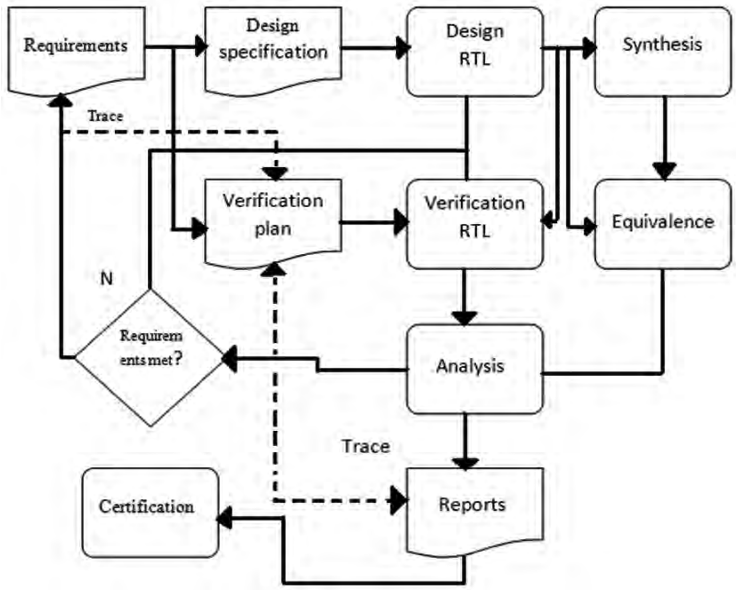


Figure 4. Typical DO-254 design flow steps[14].

implemented for software[15, 16].

For airborne equipments, FAA established a baseline for minimum design flow steps shown in Fig. 4. The process involves additional steps, particularly in the area of functional verification. It includes 5 levels of compliance termed as design assurance levels (DAL). The severity was ranged ranking from A to E[14, 17].

Where A – means failure would result in catastrophic failure of aircraft and E- means failure would not affect safety.

A DO-254-compliant design is specified using a set of formal requirements. As part of the certification process, the applicant must prove that their implementation meets all of these requirements. A graphical illustration of the typical process flow is shown in Fig. 5. Thus, the objective of DO-254 is to see whether the development and verification of complex hardware is in compliance with the mentioned process.

5. CHARACTERISATION OF LAMINATES FOR SIGNAL PROPAGATION

Laminates have a crucial role in meeting electrical performance and signal integrity. As the frequency of operation increases due to high speed and high frequency, the lines on the laminates function as part of transmission lines and transmission line model is considered which help in design of the interconnection between different pads on the PCB.

5.1 Transmission Line Model

Transmission lines are simple electrical structures that consist of an insulating layer of dielectric material sandwiched between two layers of a metal. When designing a high speed digital design, transmission lines are usually realised on a PCB which typically consist of conductive traces buried in or attached to a dielectric with one or more reference power and ground planes. The metal used is copper surrounded by suitable dielectric resin and fibre glass. The two most common types of transmission lines used in digital designs are microstrip routed on an outside layer of the PCB having one reference plane and stripline is routed on an inside layer having two reference planes. Figure 6 represents a PCB with traces routed between the various components on both internal (stripline) and external (microstrip) layers.

The phase velocity of a wave is the rate at which the phase of the wave propagates in space and it determines the delay introduced in different paths of the signal propagation.

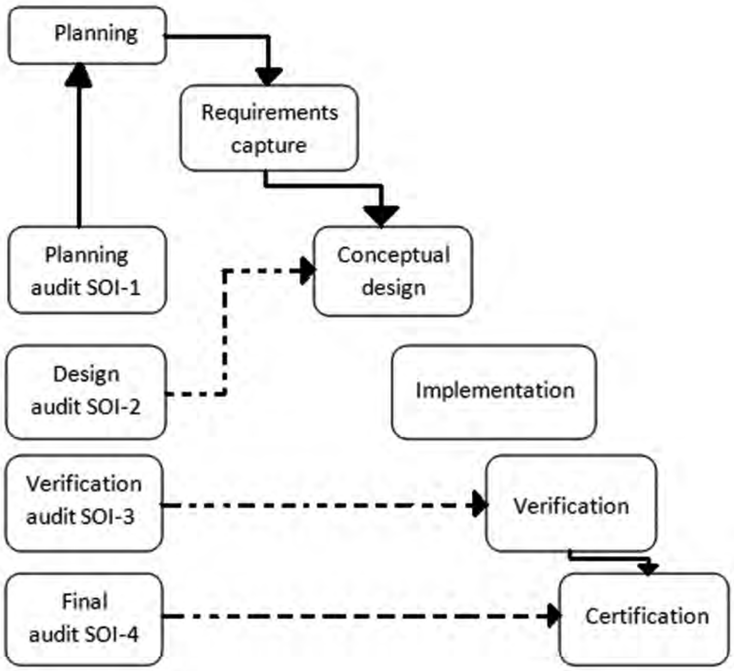


Figure 5. DO-254 process flow[14] steps.

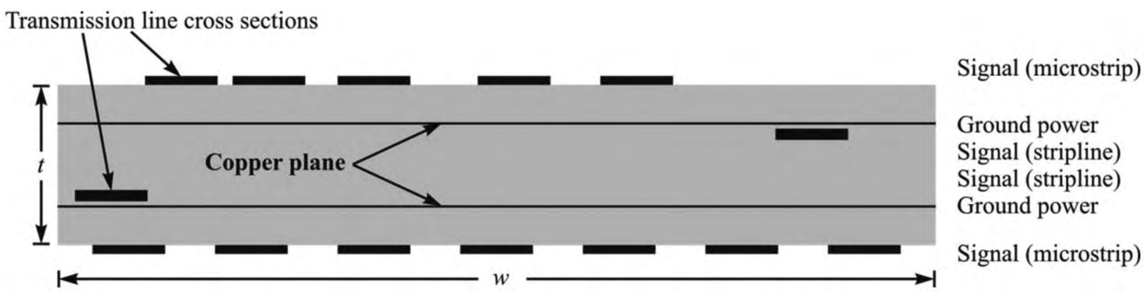


Figure 6. Typical applications of transmission lines in a digital design.

The phase velocity (V_p) of a harmonic component travelling along a transmission line in terms of L and C is:

$$V_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{LC}} \quad m/s \tag{2}$$

where, L and C are per unit length values.

Also phase velocity (V_p) can be calculated from the dielectric properties as:

$$V_p = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{3}$$

where, c is the speed of electromagnetic wave in vacuum ($3 x 10^8$ m/s); μ_r is the relative magnetic permeability of the dielectric, and ε_r is the relative permittivity of dielectric.

In selecting transmission lines for high frequency circuit application, commonly used different forms are shown in Fig. 7.

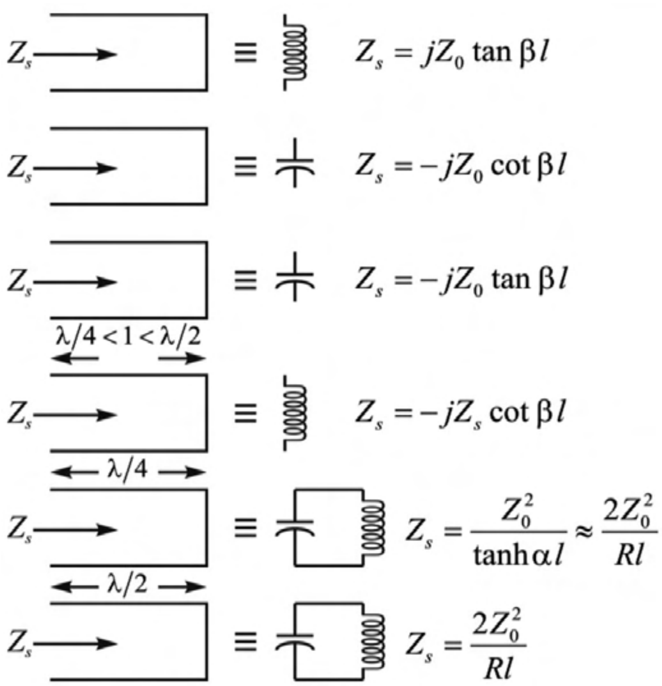


Figure 7. Input impedance of various transmission line sections.

Characteristics impedance of a loss-free transmission line in ohms is given by

$$Z_0 = \sqrt{\frac{L}{C}} \tag{4}$$

5.2 Transmission Lines Parameters for Microstrip and Coaxial Line

For the loss-free case for coaxial line, the capacitance per unit length of transmission line is

$$c = \frac{Q/l}{v} = \frac{2\pi\varepsilon}{\ln\left(\frac{b}{a}\right)} \quad F/m \tag{5}$$

The inductance per unit length of a coaxial line is given by

$$L = \frac{\ln\left(\frac{b}{a}\right)}{c^2 2\pi\varepsilon_0} \quad H/m \tag{6}$$

where, c is speed of light in vacuum and a and b are inner and outer diameters of the coaxial line.

Similarly for microstrip, the capacitance per unit length

$$c = \frac{Q}{v} = \frac{\omega}{\sum_{\substack{n=1 \\ odd}}^{\infty} A_n \sinh\left[\left(\frac{n\pi}{d}\right)h\right]} \tag{7}$$

where ω is the total charge.

Inductance per unit length with a relative dielectric permittivity of unity $(\varepsilon_r = 1)$

$$L = \frac{1}{c^2 C_{\varepsilon_{r=1}}} \tag{8}$$

where $c_{\varepsilon_{r=1}}$ is the capacitance with the relative dielectric permittivity ε_r set to 1.

5.3 Transmission Line Reflection

A change in characteristics impedance along a transmission line gives rise to reflection of the signal, resulting in voltage standing wave affecting the timing and synchronisation, thereby limiting the speed of switching from one state to zero state. The effect of reflection are computed by considering a plane electromagnetic wave propagating on transmission line A transitions to line B, where the characteristic impedance changes, two things happen: (i) a portion of the wave is reflected away from the impedance discontinuity back toward the source, and (ii) a portion of the wave is transmitted on to transmission line B, as shown in Fig. 8.

The reflection coefficient is a measure of how much is reflected back off the intersection between the two impedance regions, and the transmission coefficient gives how much of the wave is transmitted. Refection and transmission coefficients are represented by γ and T, as shown below.

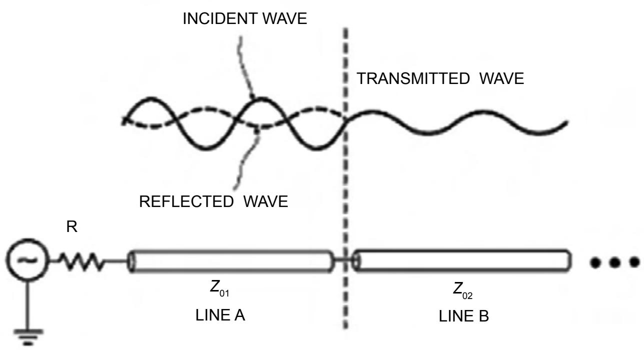


Figure 8. Computing the effect of reflection, when a signal is propagating on transmission line A and it encounters impedance discontinuously, here part will be reflected back toward the source and part will be transmitted onto transmission line B.

$$\gamma = \frac{V_r}{V_i} = \frac{Z_{02} - Z_{01}}{Z_{02} + Z_{01}} \tag{9}$$

$$T = \frac{V_t}{V_i} = \frac{2Z_{02}}{Z_{02} + Z_{01}} = 1 + \gamma \tag{10}$$

If the refection coefficient is zero, it means that the characteristic impedance in the two regions is identical. V_r and V_i are the reflected and incident voltages, and V_t is the transmitted voltage.

If the impedance discontinuity is infinite such as open circuit, the signal propagating on transmission line *A* will be reflected 100 per cent. If the impedance discontinuity is shorted to ground, the signal propagating on transmission line *A* will also be reflected by 100 per cent but will be out of phase by 180°.

5.4 Reflection from a Capacitive Load

When a transmission line is terminated in a reactive element such as capacitor, the shape of the waveforms at the driver and the load will be dependent on the value of the capacitor, the characteristics impedance of the transmission line, and any resistive terminations that may be present. At time $t = t_d$ (the delay of the transmission line) the signal reaches the capacitive load, which behaves as a short circuit producing refection coefficient of –1. The capacitor then begins to charge at a rate dependent on τ, the reflection coefficient will be 1 since the capacitor will resemble an open circuit. Equation 11 represents step response of a simple network with a time constant τ, approximates the voltage at the end of a transmission line terminated with a capacitor beginning at time $t = \tau_d$. Figure 9 shows the response of a line terminated with a capacitive load. The wave shape at node *B* follows Eqn. (11)

$$V_{capacitor} = v_{ss}\left(1 - e^{-(t-\tau_d)/\tau}\right) \text{ for } t > \tau_d \tag{11}$$

where $\tau = CZ_0$ is the time constant; τ_d is the time delay of the transmission line, and v_{ss} is the steady state voltage determined by the voltage source v_s and the voltage divider between the source resistance R_s and termination resistance R_t.

As seen from the Fig. 9(b), the waveform at the receiver (B) reaches a steady-state value of 2V after about three time constants [3τ = 3(50 Ω) (2pF=300 ps] after arriving at the receiver.

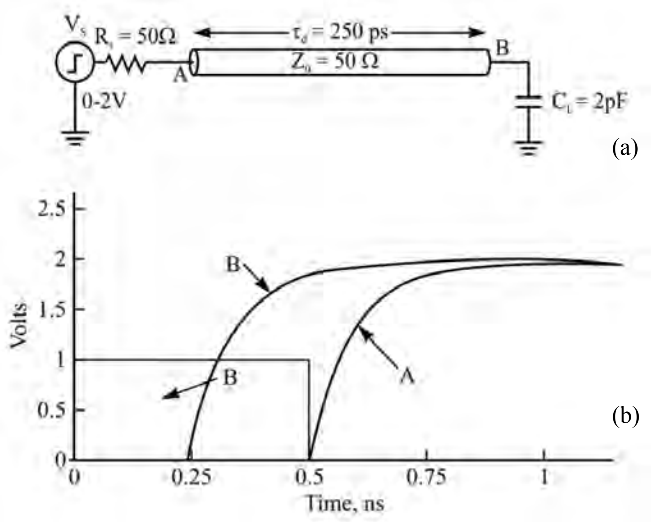
5.5 Reflection from an Inductive Load

When a series inductor appears in the electrical pathway of a transmission line termination depicted in Fig. 10(a), it will act as a time-dependent load. At time $t = \tau_d$, the inductor will resemble an open circuit and produces a reflection coefficient of 1 causing an inductive spike seen as reflection at node A in Fig. 10(b). Eventually, the inductor will discharge its energy at a rate dependent on time constant τ of an LR circuit.

For the circuit depicted in Fig. 10(a), the waveform of the rising edge at node *B* is calculated as follows

$$V_{inductor} = v_{ss}\left(1 - \exp\left[-\frac{(t-\tau_d)(Z_0 + R_t)}{L}\right]\right) \quad t > \tau_d \tag{12}$$

The wave shape calculated by Eqn. (12) will also be valid for the falling edge of the inductive spike, shown at node *B* in Fig. 10(b).



Figures 9. (a) Transmission line terminated with a capacitive load, and (b) step response showing reflections from the capacitor.

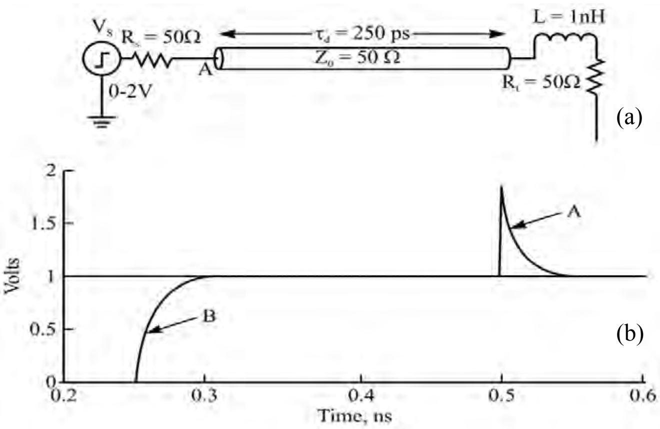


Figure 10. (a) Transmission line terminated with a series LR circuit, and (b) step response showing reflections from the inductor.

5.6 Time Domain Reflectometry

Time domain reflectometry (TDR) measurements were carried out to verify the performance of a transmission line tracks on the PCBs including transient response. Figure 11 schematically depicts a TDR set up where a fast rise step function is driven onto the PCBs under test through a 50 Ω cable. A sampling oscilloscope was used to observe the wave from at *A*, which depicts the voltage profile of the reflected waves. The voltage profile is converted to an impedance profile which is used to measure the characteristic impedance and propagation delay of a transmission line estimating inductance

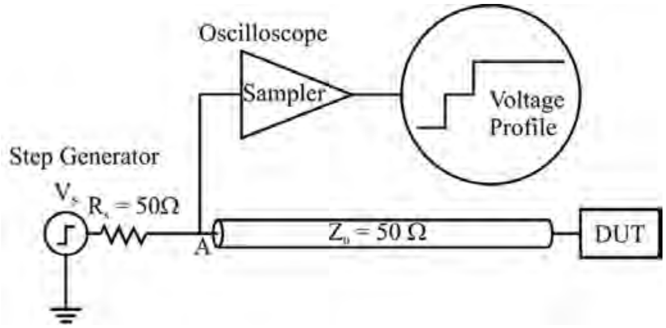


Figure 11. Generic time-domain reflectometry measurement setup.

and capacitance values of structures such as vias, bond wires and lead frames.

5.7 Non-ideal Conductor Models and Skin Depth

5.7.1 Signal Propagating in Unbounded Conductive Medium

The complex propagation constant of an electromagnetic wave travelling in a conductive medium is given by

$$\gamma = \omega\sqrt{\mu\left(\varepsilon' - j\frac{\sigma}{\omega}\right)} \qquad \varepsilon' = \varepsilon_0\varepsilon_r \tag{13}$$

The attenuation constant α and the phase constant β for electromagnetic wave propagation in a conductive medium with a conductivity of σ is as follows:

$$\alpha = \frac{\omega\sqrt{\mu\varepsilon'}}{\sqrt{2}}\left[\sqrt{1+\left(\frac{\sigma}{\varepsilon'\omega}\right)^2} - 1\right]^{1/2} \quad Np/m \tag{14}$$

$$\beta = \frac{\omega\sqrt{\mu\varepsilon'}}{\sqrt{2}}\left[\sqrt{1+\left(\frac{\sigma}{\varepsilon'\omega}\right)^2} + 1\right]^{1/2} \quad rad/m \tag{15}$$

For a perfect conductor, conductivity τ is infinite and therefore α is also infinite, and then skin depth δ must be infinitely small. Therefore, for a perfect conductor, the current only flows on the surface and the wave cannot penetrate the conductor. However, in reality, conductivity is finite due to which the current penetrates inside the surface, determined by its conductivity. At one skin depth, the field intensity and current density will be attenuated by a factor of e^{-1} eor approximately 36.7 per cent, meaning that 63.3 per cent of the current density exists within a distance of δ from the conductor surface. While selecting the quality of copper loss due to skin depth phenomenon is considered. The skin depth for copper at 1 GHz is 2.1 μ and it gets thinner at higher frequency.

6. CONCLUSIONS

Selection of appropriate laminate system for avionics industry is challenging and critical. Environment in which laminates are expected to work is continuously changing. Interconnection technology generally sets the limit of performance that can be achieved in a system. The challenge for the industry is on knowledge fusion from different cross-disciplined industries which include physics, chemistry, electrical engineering, computer engineering, mechanical engineering, material science and chemical engineering, resulting in innovative product. Laminate selection involves understanding the reaction /impact of various processes on the properties of the laminates and consequent effect on finished board performance. Optimisation of the properties and development of new laminate systems need to be carried out based on specific aerospace applications. An attempt has been made to the complexities of the laminate properties which facilitates their selection in Avionics.

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