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Design Guide for RF/ Microwave Circuit Boards

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Developed by the High Speed/High Frequency Design Task Group
(D-21b) of the High Speed/High Frequency Committee (D-20) of IPC

Supersedes:

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Users of this standard are encouraged to participate in the
development of future revisions.

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Acknowledgment

Any Standard involving a complex technology draws material from a vast number of sources. While the principal members of the High Speed/High Frequency Design Task Group (D-21b) of the High Speed/High Frequency Committee (D-20) are shown below, it is not possible to include all of those who assisted in the evolution of this standard. To each of them, the members of the IPC extend their gratitude.

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Design Guide for RF/Microwave Circuit Boards

1 GENERAL

1.1 Purpose The purpose of this document is to aid in the design of manufacturable microwave circuit boards. This document is not intended to include information relating to the detailed electrical design of microwave circuits. Rather, it is intended to include information from which practical, functional, and cost-effective circuit boards may be designed once the design engineer has determined the circuit requirements. The document also provides information on the manufacturing options available to the designer for the achievement of realistic and cost-effective circuit designs. This design aid is to be used by RF and microwave circuit design engineers, printed wiring board designers, packaging engineers, and drafters.

1.2 Scope This document addresses microwave circuitry. For the purpose of this document microwaves apply to radio waves in the frequency range of 100 MHz to 30 GHz. The document also applies to operations in the region where distributed circuits are used instead of conventional lumped circuit elements.

1.3 Terms and Definitions

Anisotropy The condition for a substance having differing values for properties, such as permittivity, depending on the direction within the material. Isotropy describes the case where a property is the same in all directions. Isotropy may exist in non-crystalline homogeneous (single phase) substances. In a microwave laminate based on a polymer composite, anisotropy of the dielectric layer exists.

Characteristic Impedance (Z_0) A transmission line parameter dependent on the distributed series impedance per unit length and the distributed shunt admittance per unit length of the transmission line. The series impedance is given by $R + j\omega L$ and the shunt admittance by $G + j\omega C$, where R, L, G , and C are the resistance, inductance, conductance, and capacitance per unit length of the transmission line, j is $\sqrt{-1}$ and ω is the angular frequency. The characteristic impedance, Z_0 , is the square root of the ratio of the impedance to the admittance.

Coaxial Cable (Coax) A transmission line (see Transmission Line) structure where a round signal conductor centered coaxially inside a round tubular return (ground) conductor. The inside diameter of the return conductor is greater than the outside diameter of the signal conductor.

Coefficient of Thermal Expansion (CTE) The linear dimensional change of a material per unit change in temperature.

Copper Weight The mass of copper per unit area for a foil. The copper foil industry typically expresses weight in ounces per square foot (oz/ft^2). A copper foil weight of $1 \text{ oz}/\text{ft}^2$ corresponds to a nominal $34 \mu\text{m}$ [$1350 \mu\text{in}$] thickness. This designation is being replaced by thickness in micrometers (μm). (See IPC-4562.)

Copper Thickness The thickness dimension of the copper cladding on a laminate.

Dielectric A material that has a zero or nearly zero electrical conductivity.

Dielectric Constant See definitions of Relative Permittivity, Static Relative Permittivity, and Effective Permittivity.

Dielectric Thickness Thickness dimension of the dielectric of the laminate averaged over an area.

Directional Coupler A device or structure which causes some of the energy propagating along one transmission line to be transferred to a second transmission line so that most of the transferred energy propagates in a specific direction along the second line. The other direction is considered isolated. At lower frequencies this function can be accomplished in a design with lumped capacitive and inductive elements while at microwave frequencies two stripline or microstrip traces that run parallel to each other for a certain distance can serve the purpose. One use for such devices is to sample amplitude or phase of a signal traveling in a specific direction.

Directivity The difference between the isolation and the coupling values of a directional coupler.

Dissipation Factor The ratio of loss current to charging current. The dissipation factor or loss tangent, $\tan\delta$, is given by ϵ''/ϵ' , where ϵ' and ϵ'' are the real and imaginary parts of the permittivity (see Permittivity). The loss tangent is a parameter used to express the tendency of insulators or dielectrics to absorb some of the energy in an ac signal.

Distributed Component An electrical component with dimensions greater than or on the order of the wavelength of the propagating signal. The reactive and resistive electrical characteristics of such a component are said to be distributed.

Effective Permittivity (effective dielectric constant or ϵ_{eff}) The permittivity of a mixed media configuration, such as air and the solid dielectrics used in microstrip, that has the equivalent electromagnetic wave propagation characteristics of a single dielectric medium.

Ground Plane An electrically conductive metal layer within a printed wiring board that provides a low inductance ground reference (return path) to signal traces.

on adjacent or buried lines. The ground plane also provides a ground connection for active and passive devices.

Ground-to-Ground-Spacing Distance between ground planes in a stripline circuit.

Ground-to-Signal-Spacing Distance between ground and signal planes or conductors in a transmission line.

Impedance A measure of the opposition to the flow of alternating current in a circuit, equal to the ratio of the rms electromotive force in the circuit to the rms current produced by it. Impedance is usually represented in complex notation as $Z = R + jX$, where R is the ohmic resistance, X is the reactive, either inductive or capacitive, and j is $\sqrt{-1}$.

Insertion Loss The ratio of transmitted electromagnetic power to incident power, usually expressed logarithmically in decibel (dB) units. This loss of power includes losses by conversion to heat in the dielectric and in the conductors.

Loss Tangent See Dissipation Factor.

Lumped Circuit elements that are not distributed.

Metallization A deposited or plated thin metallic film that is used for its protective and/or electrical properties.

Microstrip A transmission line (see Transmission Line) structure that consists of a signal conductor that runs parallel to and is separated from a much wider ground plane.

Microwave Laminate A laminate of metal cladding on dielectric substrate of composition selected to be suitable for circuit boards intended for operation at microwave frequencies.

Microwaves A term generally applied to radio waves in the frequency range of 1 GHz to 100 GHz. It generally refers to the frequency range where circuits and device interconnects are described as distributed elements instead of lumped elements.

Open Circuit A high impedance condition that ideally exhibits 0 dB return loss and a reflection coefficient of 1.0.

Peel Strength The force per unit width that is required to peel a conductor foil from a laminate perpendicular to the surface of the substrate.

Permittivity The square root of the ratio of the electromagnetic wave propagation characteristics of free space to that of the dielectric medium. The permittivity, ϵ , of a material is, in general, a complex-valued (has real and imaginary parts) parameter. The real and imaginary parts of ϵ are given by ϵ' and ϵ'' . See definitions of Relative Permittivity, Static Relative Permittivity, Effective Permittivity.

Plated-Through Holes A hole with plating on its walls that makes an electrical connection between conductive patterns on internal layers, external layers, or both, of a printed circuit board.

PTFE Polytetrafluoroethylene.

Reflection Coefficient The percentage of power (or voltage) reflected from a load that is attached to a circuit or transmission line.

Relative Permittivity (ϵ_r) The relative permittivity, ϵ_r , is the ratio of the permittivity of a material to that of free space. The relative permittivity is a complex-valued parameter and is given by: $\epsilon_r = \epsilon/\epsilon_0$, where ϵ_0 is the permittivity of free space (which is a real value). The real and imaginary parts of ϵ_r are ϵ'_r and ϵ''_r . Herein ϵ_r denotes the real part of the complex relative permittivity of the dielectric.

Return Loss Level of the reflected signal which is a result of a mismatch between a load and a source. It is usually expressed as the ratio of reflected power to incident power in dB units.

Static Relative Permittivity The ratio of the capacitance (C_x) of a given configuration of electrodes with a specified dielectric, filling all the region of electropotential field, to the capacitance (C_v) of the same electrode configuration with a vacuum (or air) as the dielectric.

S-Parameters Parameters used to describe the operations of a microwave circuit: S11 is the input reflection coefficient, S22 is the output reflection coefficient, S21 is the forward transmission, and S12 is the reverse transmission.

Semi-Rigid Cable A coaxial cable that has a solid outer conductor.

Short Circuit A low impedance that ideally exhibits 0 dB return loss and a reflection coefficient of -1.0.

Skin Depth The depth into a conductor for which e^{-1} of the current associated with a propagating electromagnetic signal is flowing. The depth becomes less as frequency increases and so resistive loss also increases. e is the base for natural logarithms and is approximately 2.7183.

Skin Effect The increase in resistance of a conductor at microwave frequencies that is caused by the tendency of electrical current to concentrate at the conductor's surface (see Skin Depth).

Smith Chart A transmission line calculator used to evaluate and analyze microwave circuitry.

Stripline A transmission line (see Transmission Line) structure that consists of a signal line that runs parallel to and is sandwiched between and separated from two wider ground planes.

Soft Substrate For the purpose of this document the term soft substrate refers to the materials specified in IPC-4103.

TEM Mode (Transverse Electromagnetic Mode) A mode of electromagnetic wave propagation in which, at any point along the line, the electrical and magnetic fields

fields both lie in a plane perpendicular to the direction of propagation. This efficient mode is characteristic of free space and is favored by coaxial and stripline transmission lines up to a frequency where other modes, with propagation characteristics different from that of the TEM mode, can exist. The frequency at which these other modes can exist is dependent on frequency and the dimensions of the line perpendicular to the direction of wave propagation.

Transmission Line A device for guiding or conducting electromagnetic energy from one point to another. A transmission line consists of two or more parallel conductors each separated by a dielectric.

VSWR Voltage Standing Wave Ratio, a measure of the degree of mismatch between a load and a transmission line.

Wavelength The distance an electromagnetic wave propagates during one full cycle. It is the ratio of the propagation velocity in length units per unit time to the frequency in cycles per unit time.

2 APPLICABLE DOCUMENTS

The following specifications of the revision in effect at the time of order form a part of this document to the extent specified herein.

2.1 IPC¹

IPC-T-50 Terms and Definitions for Interconnecting and Packaging Electronic Circuits

IPC-D-325 Documentation Requirements for Printed Boards

IPC-2221 Generic Standard on Printed Board Design

IPC-2615 Printed Board Dimensions and Tolerances

IPC-4103 Specification for Base Materials for High Speed/High Frequency Applications

IPC-4562 Metal Foil for Printed Wiring Application

IPC-6018 Microwave End Product Board Inspection and Test

IPC-9191 General Guidelines for Implementation of Statistical Process Control (SPC)

J-STD-003 Solderability Test Methods for Printed Circuit Boards

1. www.ipc.org
2. www.astm.org
3. www.sae.org
4. www.asme.org
5. www.iso.ch

2.2 American Society for Testing and Materials²

ASTM B-488-95 Standard Specification for Electrodeposited Coatings of Gold for Engineering Use

2.3 Society of Automotive Engineers³

SAE AMS-C-5541 Chemical Conversion Coatings on Aluminum and Aluminum Alloys

SAE AMS-P-81728 Plating, Tin/Lead (Electrodeposited)

2.4 American Society of Mechanical Engineers⁴

ASME-Y-14.100 Engineering Drawing Practices

2.5 International Organization for Standardization⁵

ISO 9001 Quality Management

2.6 Reference Information Software, which is commercially available, can be used when designing microwave boards.

3 DESIGN CONSIDERATIONS

Figure 3-1 shows the major steps in the microwave circuit design process. These steps are explained in the following subsections.

3.1 Initial Input The complete performance characteristics of the product are defined together with the environmental requirements, cost goals, size and weight constraints, and other pertinent information affecting the design. Administrative input comprises completion date, available financial and personnel resources, and expected delivery times for potential materials and components to be used in the design.

3.2 Design Options A literature search is made for similar product designs. These design options are listed with their expected performance specifications, and the most appropriate design is selected as the starting point.

3.3 Transmission Line Type, Materials, and Components The transmission line type (such as microstrip, stripline, suspended substrate, etc.), substrate type, and components are selected. An estimate of the electrical performance is made and compared to the design specification. If the design specification is not met, the design process loops back to select another design option.

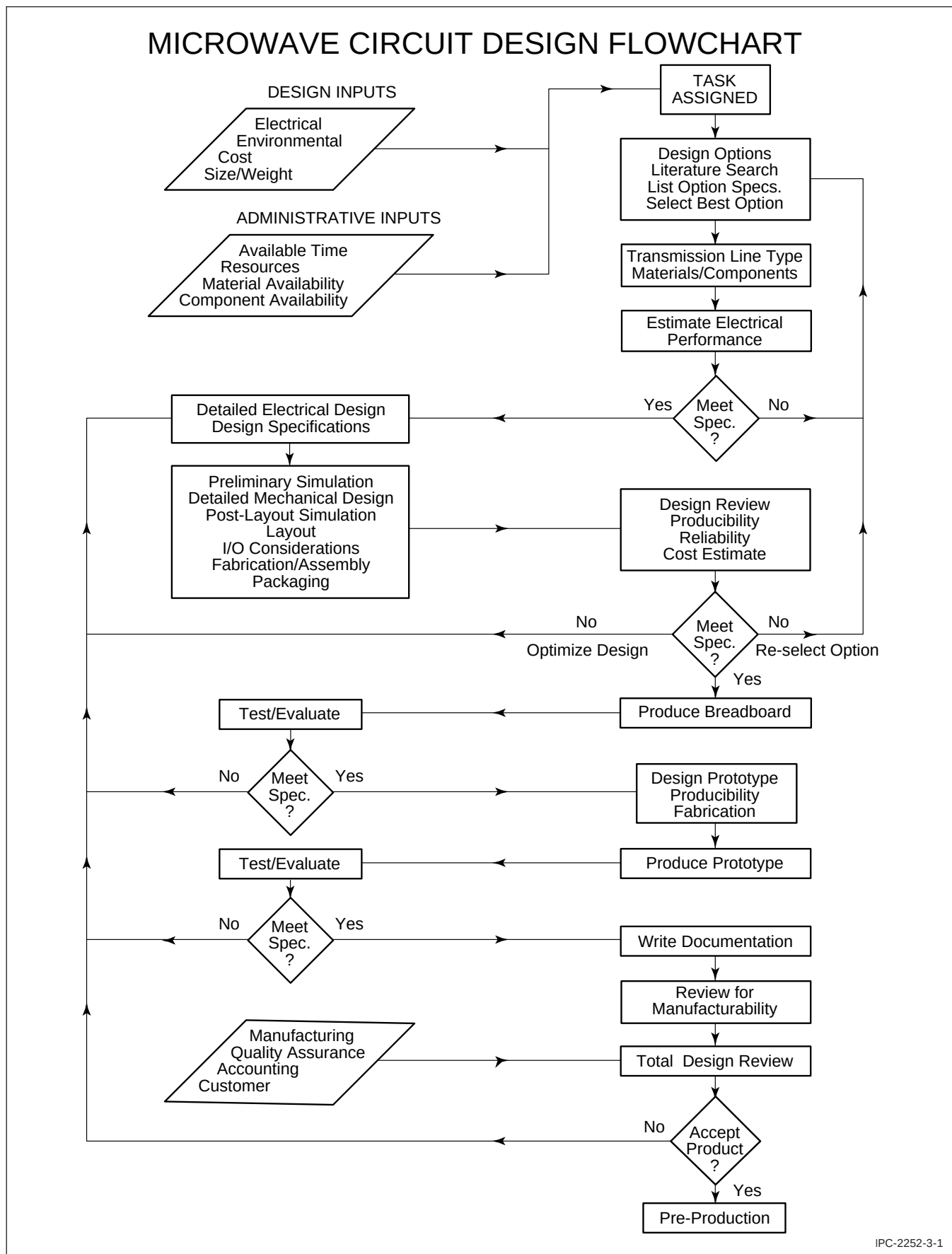


Figure 3-1 Microwave Circuit Design Flowchart

3.4 Electrical Design Detailed electrical design calculations are done to find values for all circuit features and components, and a complete circuit diagram is completed.

3.5 Mechanical Design Electrical values are realized (converted to line dimensions), and a circuit layout constructed. Input/output connection considerations, fabrication, assembly and packaging needs must be considered in designing the layout. A tolerance analysis should be made at this point.

3.6 Preliminary Design Review The preliminary design is reviewed for produceability and reliability, and a preliminary cost estimate made. Electrical performance is re-calculated and these data are compared to the product specification. If the specification is not met, a decision must be made to either select another design option, or to optimize the existing design.

3.7 Breadboard A breadboard simulation of the design is constructed and electrically tested. Output performance is compared to the design specification. If the design specification is not met, the design process loops back to the detailed electrical design.

3.8 Prototype A prototype of the design is made using the exact materials, components, and fabrication processes used for the circuit design. The prototype is fully electrically and mechanically tested under the product environmental specification conditions. Test results are compared to the product specification. If the specification is not met, the design process loops back to the detailed electrical design.

3.9 Documentation The product and manufacturing processes are fully documented, including drawings, purchasing specifications, and Quality Assurance Provisions. The documentation and product control are turned over to manufacturing.

3.10 Final Design Review The design is given a final review with input from internal departments and the customer. If the product is not accepted, control is returned to the design group and the design process loops back to the detailed electrical design. Otherwise, manufacturing retains control and the product goes into pre-production.

4 DOCUMENTATION REQUIREMENTS

4.1 Design Features Listing Circuit boards designed using this Guide should meet or exceed the requirements of IPC-6018, internal company documents, or the contract. Coupon configuration should be per IPC-6018 unless otherwise defined on the master drawing. Test coupons should represent all the printed circuit board manufacturing pro-

cesses such as drilling, plating, etching, fusing, ground/voltage/thermal/mechanical planes, etc.

Test circuitry, when provided, should be included on the production master and on each panel to be manufactured.

4.2 Master Drawing The master drawing should be prepared in accordance with IPC-D-325, or, in the case of a military contract, ASME-Y-14.100. The master drawing should include all appropriate detail board requirements including, but not restricted to, the following:

- a. The type, size and shape of the printed circuit board.
- b. The size, location, and tolerance of all holes, slots, and internal routed areas.
- c. Thickness of the dielectric separation between layers. In multilayer boards, consider thickness of bonding films.
- d. Shape and arrangement of both conductive and nonconductive patterns defined on each layer of the printed circuit board.
- e. Separate views of each conductor layer.
- f. A modular grid system to identify all holes, test points, lands and overall board dimensions with modular units of length of 2.5 mm [0.100 in], 1.25 mm [0.050 in], 0.625 mm [0.025 in], or other multiples of 0.125 mm [0.005 in] in that order of preference. The grid system should be applied in the X and Y axes of the Cartesian coordinates. The grid system should not be reproduced on the master drawing, but may be indicated using grid scales or X-Y control dimensions.
- g. Any and all patterned, drilled, or routed features not controlled by hole sizes and locations should be dimensioned either specifically or by reference to the grid system.
- h. Include all notes starting on the first sheet of the master drawing.
- i. Conductor layers numbered consecutively starting with the component side or ground side routed through to accommodate component mounting as layer 1.
- j. The identification marking and location of traceability marking.
- k. The dimensions for critical pattern features that may affect circuit performance because of distributed inductive or capacitive effects within the tolerance required for circuit performance.
- l. All terms used on the master drawing should be in conformance with the definitions of IPC-T-50 or IPC-2615.
- m. The minimum line width and spacing of the finished printed circuit board.
- n. The plating and coating materials and thickness. Particular attention must be paid to defining plated-through holes and plated edges.



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- o. Applicable fabrication specifications.
- p. The relative permittivity (ϵ_r), $\tan\delta$, etc of substrate. (Reference IPC-4103).
- q. The type and thickness of copper. (Reference IPC-4103).
- r. The type and thickness of bonding films.

4.3 Master Pattern The printed circuit board documentation package usually consists of the master drawing, master pattern drawing, or copies of the artwork masters (film or electronic data). This documentation should meet the requirements of IPC-D-325. Documentation for Military boards should meet the requirements of ASME-Y-14.100. Other documentation, in addition to electronic data for artwork, may include NC tape or electronic data for drilling, routing, testing, and panelization.

When a production master is not supplied, the supplier will be responsible for the preparation of the production master with sufficient accuracy to meet the requirements of the printed circuit detailed on the master drawing. It is recommended that the accuracy of the production master (single image, multiple image and/or any associated test coupons) should be such that the lands, conductors and other features be located within 0.050 mm [0.002 in] diameter of the true grid position established for the layer. In the event that smaller tolerances are required in order to produce critical printed circuits, the production master precision requirements, as considered in the design process, should be defined on the master drawing.

5 MATERIALS

5.1 Microwave Printed Circuit Board Materials Table 5-1 lists typical microwave materials, including the resin system, reinforcement type, typical values of relative permittivity and maximum loss tangent at X-band frequencies (5.20 GHz to 10.90 GHz). A complete listing of the materials and their specifications that are suited for high-speed and high-frequency applications can be found in IPC-4103.

5.1.1 Substrate Selection Since selection of the substrate is made early in the design process it is important to

choose the correct substrate to avoid subsequent costly and time-consuming re-design using a different substrate. The major considerations for substrate selection are described in the following subsections.

5.1.1.1 Relative Permittivity The relative permittivity of the substrate must be high enough to permit the manufacture of devices that meet both space and weight limitations. That is, resonant elements must be small enough and any delay lines must be short enough and line widths narrow enough (with the appropriate line-to-line spacing to achieve the required electrical isolation) to fit within the maximum allowable dimensions.

For other applications, such as high-speed interconnects, the relative permittivity must be low enough to allow manufacture of high impedance circuit lines having acceptable line width and characteristic impedance tolerances.

Line widths for a range of board thicknesses, wavelengths for the operating frequencies of the circuit, and estimations of circuit element dimensions should be determined, and a rough layout of the circuit board should be made to determine the maximum and minimum acceptable values of relative permittivity.

The substrate manufacturer's stated tolerance in relative permittivity must be small enough to allow the electrical performance of the circuit to remain within its specified tolerance limits.

5.1.1.2 Loss Tangent Dielectric loss in dB/m for microwave circuit boards is given by:

for stripline designs [1]:

$$\alpha_{d, \text{strip}} = 27.3 \sqrt{\epsilon_r} \frac{\tan\delta}{\lambda},$$

for microstrip designs [1]:

$$\alpha_{d, \text{micro}} = 27.3 \frac{\epsilon_r}{\epsilon_r - 1} \frac{\epsilon_{r, \text{eff}} - 1}{\sqrt{\epsilon_{r, \text{eff}}}} \frac{\tan\delta}{\lambda},$$

Table 5-1 Typical Microwave Materials

Material Type	Relative Permittivity, ϵ_r	Loss Tangent, $\tan\delta$	IPC-4103 Specification Sheet
Woven Glass Reinforced PTFE	2.40 to 2.60	0.0025	/02
Random Glass Reinforced PTFE	2.15 to 2.35	0.0015	/04
Woven Glass Reinforced PTFE	2.15 to 2.35	0.0015	/05
Ceramic Filled PTFE	3.0, maximum	0.0017 to 0.003 (depending on ϵ_r)	/06
Ceramic Filled PTFE	5.0 to 7.0	0.003	/07
Ceramic Filled PTFE	8.5 to 11.0	0.0035	/08



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