Design and Technology Tradeoffs in Passive RF and Microwave Integrated Circuits

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This article examines the choices an engineer must make when deciding how to achieve an integrated microwave or RF circuit using available fabrication and packaging methods

Designers of RF and microwave integrated circuits often go through numerous design iterations. The tradeoff design process reduces unnecessary costs and design iterations, thus allowing designers time to improve the quality of the product.

Modern technology for RF and microwave integrated circuits (ICs) provides smaller size, lighter weight, and lower cost. Passive components play a key role in RF designs for performance matching, tuning, filtering, and biasing. Passive components are prevalent in RF and microwave IC. For example, it is estimated that in a single-mode wireless phone, passive components account for 90% of the component count, 80% of the size, and 70% of the cost [1]. RF and microwave ICs are usually based on these passive printed components: directional couplers, baluns, power dividers/combiners, filters, phase shifters, ferrite isolators/circulators, and duplexers. In this paper we will consider the design tradeoffs for passive printed RF and microwave components using various technology processes.

The design flow chart for print RF and microwave passive components, including technology process, is shown in Figure 1. The first step of the design flow is preparing system level requirements. For each requirement, a designer has to choose an integer value of weighting coefficient k_i (the second step of the flow chart Fig. 1a), starting with $k = 1$ for the most important parameter [2]. The third step of the flow chart is the selection of the printed transmission line which has been described, for example, in [2]. The forth step of the flow chart (see Fig. 1b) includes selection of technology process, substrate, conductor, dielectric and resistive materials, as well as the selection of number of layers. Tradeoff design of printed RF and microwave ICs includes consideration of several contradictory parameters: volume vs. loss, cost vs. volume, loss vs. cost, volume vs. power, cost vs. temperature range, cost vs. power, shielding vs. cost, bandwidth vs. cost, environmental vs. volume, environmental vs. cost.

The selection of a printed RF and microwave component prototype (fifth step of the design flow, Fig. 1a) includes analysis, synthesis, and optimization of the optimal integrated circuit. Synthesis of a printed component is then based on the requirements. Synthesis results are physical dimensions of the print component. Analysis of the printed component entails definition of electrical performance for given physical dimensions. An electromagnetic simulation may be used to create an S-parameter model of a printed component. The parameters of the printed component can be simulated using Agilent's ADS or other EDA tools. In this case, a designer has to set up variable parameters that can be used to optimize the printed component. Analysis of manufacturing tolerances should be considered to avoid excessive manufacturing cost. This analysis is especially critical for higher frequencies. There are commercial electromagnetic (EM) modeling tools from such companies as Agilent-EEsof, Ansoft, Applied Wave Research, Computer Simulation Technology, Sonnet Software, Zeland Software, and others.

The novel CAD "PRINTCIRCOMPTECH" (print circuit components/technology) is an

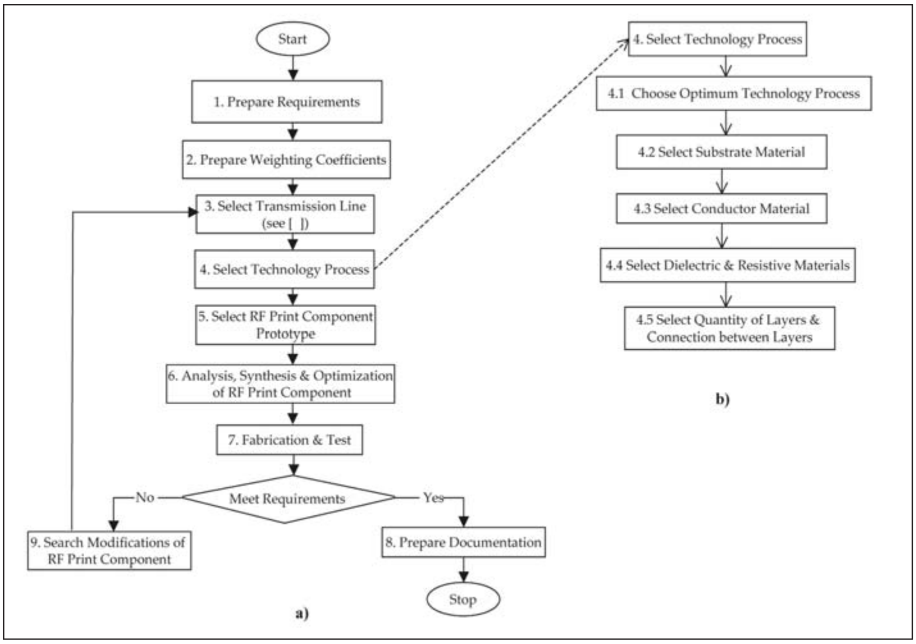

Figure 1 · Passive integrated circuit tradeoff analysis flow chart.

easy-to-use program that creates documentations for different kinds of RF and microwave passive components and technology processes. The program provides for synthesis, analysis, and optimization of passive components with known electrical, environmental, mechanical, and application requirements. An output documentation of the PRINTCOMPTECH includes physical dimensions of a component, electrical performance, optimum technology process and materials, and tolerance analysis. RF and microwave integrated IC can be divided into three categories: hybrid IC, monolithic IC, and a combination of hybrid and monolithic IC.

PRINTCOMPTECH includes the following four different input/output versions:

- Version 1
  INPUT: requirements, unknown print component, unknown technology process and materials;
  OUTPUT: optimum print component type and performance, optimum technology process and materials, tolerances analysis, compliance between performance and requirements.
- Version 2
  INPUT: requirements, known print component, unknown technology process and materials;
  OUTPUT: optimum print component type and performance, optimum technology process and materials, tolerances analysis, compliance between performance and requirements.
- Version 3
  INPUT: requirements, unknown print component, known technology process and materials;
  OUTPUT: optimum printed component type and performance, tolerances analysis, compliance between performance and requirements.
- Version 4
  INPUT: requirements, known print component, known technology process and materials;
  OUTPUT: optimum print component type and performance, tolerances analysis, compliance between performance and requirements.

Table 1 represents OUTPUT information for the known technology process and materials as a result of analysis (Version 4) and synthesis (Version 3) of print RF and microwave components.

If technology process and materials are unknown (Version 1 or Version 2), the OUTPUT information includes technology process type, quantity of layers, substrate material, conductor, resistive and additional dielectric materials, package type and material.

Electrical characteristics of regular *transmission lines* for RF and microwave IC are: loss (conductor, dielectric, and radiation), quality factor, impedance, effective dielectric constant, guide wavelength, operating bandwidth, cutoff frequency, wave propagation (fundamental mode), polarization, maximum operating frequency, radiation, and dispersion. Existing print transmission lines have some limitations (see Table 2) which influence the tradeoff design results.

The program TRASLTECH (transmission line/technology), which is part of PRINTCIRCOMPTECH, includes the following print transmission lines [2, 3]:

· Microstrip line (ML), shielded ML, inverted ML, suspended ML, microslab, embedded ML, coated ML, thin-film ML, membrane supported ML
· Stripline (SL), double-conductor SL
· Suspended stripline (SSL), shielded high-Q SSL, double-substrate SSL
· Slotline (SLL), bilateral SLL, antipodal SLL
· Coplanar waveguide (CPW), shielded CPW, grounded CPW
· Finline (FL), bilateral FL, antipodal FL, antipodal overlapping FL
· Coplanar Strips (CS)
· Broadside Strips (BS)

Combining various printed transmission lines [3] is one way to solve RF and microwave system complexity and provide tradeoff design, high level of miniaturization, and design of novel components with better performance. There are combinations of balanced and unbalanced transmission lines (baluns), regular lines and coupled lines, low-loss and high loss lines, high-Q and miniature lines [4].

Let us consider some aspects of the ML tradeoff design. Choosing physical dimensions of ML is a good example of the tradeoff design. Dimensions of microstrip components decrease with increasing dielectric constant of the substrate. Losses then usually increase because higher dielectric constant materials usually have higher loss tangents, and also because for the same characteristic impedance, reduced conductor line widths have higher ohmic losses. This is a typical conflict between the simultaneous requirements of small dimensions and low loss.

Factors that affect the choice of substrate thickness are most controversial. The positive effects of decreasing substrate thickness are: compact components, ease of integration, less tendency to emit higher-order modes of radiation, smaller parasitic inductances produced by via holes drilled through the dielectric substrate. However, a decrease in substrate thickness, while maintaining constant characteristic impedance, must be accompanied by a narrowing of the conductor width. Narrowing the width leads to higher conductor losses along with a lower Q-factor. Also, for smaller width and thickness, fabrication tolerances become more severe. Careless handling of thin substrates can cause stress and strain, which can modify the performance of the substrate. The strip width of ML should be minimized in order to decrease the overall dimensions, as well as to suppress higher-order modes. It is important to remember, however, that a smaller strip width leads to higher losses and stronger width tolerance.

Print RF Component	OUTPUTS	
	Version 4 (Analysis)	Version 3 (Synthesis)
Transmission Line	impedance, loss, *VSWR*, cutoff frequency, dispersion, effective dielectric constant, guide wavelength, power, frequency range, bandwidth	conductor physical dimensions (width & THK), substrate THK, housing size, space between conductors
Directional Coupler	directivity level and type, coupling, VSWR, loss, isolation, impedance of segments, amplitude & phase balance, input/output impedance, guide wavelength, power, frequency range, bandwidth	conductor physical dimensions (width, length, THK); space between conductors, substrate THK
Divider/Combiner	power ratio, impedance of segments, isolation, loss, *VSWR*, input/output impedance, amplitude & phase balance, guide wavelength, power, number of channels, frequency range, bandwidth	conductor physical dimensions (width, length, THK); space between conductors, substrate THK, resistor dimensions & configuration (for Wilkinson divider)
Filter	pass band attenuation, ripples, order, stop band attenuation, second/third-harmonic attenuation, *VSWR*, frequency selection, frequency response, phase response, group-delay, impedance of resonators, input/output impedance, guide wavelength, power, cutoff frequency, frequency range, passband	structure, resonator physical dimensions (width, length, THK); space between resonators, substrate THK
Balun	isolation, loss, *VSWR*, impedance of segments, input/output impedance, guide wavelength, power, frequency range, bandwidth	structure, conductor physical dimensions (width, length, THK); substrate THK
Phase Shifter	phase shifter type, phase shift, phase shift error, loss, *VSWR*, impedance of segments, input/output impedance, guide wavelength, guide wavelength, power, frequency range, bandwidth	structure, conductor physical dimensions (width, length, THK); substrate THK
Ferrite Isolator/Circulator	isolation, loss, *VSWR*, impedance of segments, mode operation, saturation magnetization, effective permeability, direction of circulation, magnetic field strength, mode operation, input/output impedance, guide wavelength, power, frequency range, bandwidth	resonator dimensions & configuration, ferrite configuration, magnet configuration, substrate THK
Duplexer	isolation, loss, *VSWR*, impedance of segments, input/output impedance, guide wavelength, power, frequency range, bandwidth	structure, conductor physical dimensions (width, length, THK); substrate THK

Table 1 · OUTPUTs of different RF and microwave components for analysis and synthesis (technology process and materials are known).

Another example of the tradeoff design is choosing physical dimensions of the high-Q SSL. Large height (distance between top and bottom ground planes) leads to a higher power capability and a higher Q-factor of the SSL. The strip width should be decreased in order to decrease the overall dimensions, as well as to suppress the high modes. It is important to remember, however, that a smaller strip width leads to higher losses. Also, a smaller strip requires a smaller height for the same impedance.

Technology processes determine the following characteristics of passive print RF and microwave components: losses, maximum power, frequency range, cost, and size. According to the program PRINT-COMPTECH, the choices for the technology process are [3, 5, 6]: 1) Printed Circuit Board (PCB); 2) Thick-Film; 3) Thin-Film; 4) Low-Temperature Co-fired Ceramic (LTCC); 5) Direct Bond Copper (DBC); 6) Monolithic.

1. *The PCB* is used to etch the required patterns on the copper laminated plastic substrates. The most common processes used in the fabrication of PCB are plating, bonding, etching, and drilling. There are some limitations of PCB technology: the typical limit of track width and minimum gap between two conductors is around 5-10 mil and the typical tolerance of the conductor width is 1 mil.

2. *Thick-film technology* includes printing, baking, and trimming processes. Special pastes are placed on a screen with areas opened for the circuit pattern. Conductive pastes (silver, gold, palladium-gold, and so forth) are used for conductors, resistive paste is used for resistors, and dielectric pastes (Al_2O_3, AlN, and BeO) are used for capacitors and coupled lines. Advantages of this technology are low cost, possibility of mass production, potential for multilayer circuit structures. But the thick-film technology has difficulties of fabrication of fine lines and gaps.

3. *Thin-film technology* involves sputtering a metal (chromium, nickel, and so forth) that has good adhesive performance with substrate to form a thin adhesive layer. The next step is sputtering a layer of gold. The next step is the optical printing. Thin-film passive integration technology is attractive because it is accurate and capable of achieving higher capacitance densities, while lower process tolerances are required. Thin-film technology provides discrete capacitors and inductors with are high Q, low ESR, and very precise values for capacitance (±0.01 pF) and inductance (±0.1 nH). For coupled line components, finer line widths maximize the coupling coefficient, making possible the 3-dB couplers.

4. *LTCC technology* is a low-cost multilayer ceramic process for fabrication of RF and microwave components. Conductive, dielectric, and resistive pastes are applied on each ceramic sheet. This technology uses thin layers of ceramic substrates with printed conductors to realize transmission lines, distributed components, and other structures. The numerous sheets are then inspected, assembled, laminated together, and co-fired at around +850ºC. Plated-through vias are used for inter-layer interconnection. Multi-layer design allows for realization of innovative printed structures such as baluns and filters. Advantages of the LTCC technology are low cost, low loss, high yield, precisely defined parameters, high performance conductors, potential for multi-layer structures, and high density.

5. *DBC process* is used for directly bonding the copper sheet to the ceramic or ferrite substrate, after which a pattern is formed thereon by masking and etching. The results are

Transmission Line	Impedance (Ohm)	Frequency Band	Bandwidth (%)	Dispersion	Relative Loss	Low-Cost Production	Chip Mounting
Stripline (SL)	15 - 250	VHF, UHF, L, S, C, X	0.1 – 20.0	none	moderate	good	poor
Suspended Stripline (SSL)	30 - 150	L, S, C, X , Ku, K, Ka, Q	0.1 -1000.0	none	low	fair	fair
Microstrip Line (ML)	15 - 120	VHF, UHF, L, S, C, X	0.1 -1000.0	low	moderate	good	difficult for shunt; easy for series
Slotline (SLL)	30 – 200	VHF, UHF, L, S, C, X, Ku, K, Ka, Q	0.1 – 20.0	high	high	good	easy for shunt, difficult for series
Coplanar Waveguide (CPW)	25 - 160	VHF, UHF, L, S, C, X, Ku, K, Ka, Q	0.1 -1000.0	low	high	good	easy for series & shunt
Finline (FL)	10 - 400	Ka, Q, E, F, G	0.1 -1000.0	low	low	fair	fair

Table 2 · Printed transmission line limitations

Technology Process	Width & Space Tolerance (Depends on Input $l = \Lambda/4$ tolerance) (mil)	Min Width & Space (mil)	Substrate THK (inch)
PCB	+/- 0.5 to +/- 1.0	5.0	0.005 - 0.150
Thick Film	+/- 0.5	3.0	0.01- 0.06
Thin Film	+/- 0.1 to +/- 0.5	0.6 – 3.0	0.005 – 0.04
LTCC	+/- 0.4	4.0	0.004 – 0.04
DBC	+/- 1.0	7.0	0.01 – 0.06

Table 3 · Selection of technology process according to transmission line dimensions, tolerances, and minimum dimensions.

Technology Process	Cost		
	Low	Medium	High
PCB	low to high QTY		
Thick Film		low to high QTY	
Thin Film			medium to high QTY
LTCC		medium to high QTY	
DBC		medium to high QTY	
Monolithic	high QTY		low QTY

Table 4 · Selection of technology process according to cost/Qty.

Technology Process	RF Power		
	High	Medium	Low
PCB	-	+	+
Thick Film	-	+	+
Thin Film	-	+	+
LTCC	-	+	+
DBC	+	+	+
Monolithic	-	-	+

Table 5 · Selection of technology process according to maximum RF power.

Technology Process	Integration Level		
	High	Medium	Low
PCB	-	+	-
Thick Film	-	+	-
Thin Film	+	-	-
LTCC	+	-	-
DBC	-	-	+
Monolithic	+	-	-

Table 6 · Integration level of different technology processes.

high power possibility and extremely strong bond of high-conductivity copper to the substrate.

6. *Monolithic process* uses a high-volume semiconductor technique when active and passive devices are grown and deposited on common semi-insulating substrate. Such circuits are produced by the processes of epitaxial growth, ion implantation, masked impurity diffusion, oxide growth, and oxide etching. The monolithic technology provides small size and weight, less parasitic reactance than discrete devices, broader bandwidth than hybrid circuits, and reproducible results, especially for the same wafer. Monolithic technology also provides extremely high operating frequencies at low noise level. Disadvantages of monolithic technology are the expensive semiconductor substrate (which is especially noticeable for small quantities produced), very tight processing steps and tolerances, limited heat dissipation, and a low Q-factor of resonators and filters.

The choice of technology process depends on various parameters: electrical performance, quantity of units produced, manufacturing tolerances, cost, required integration level, etc. Comparison of performances for different technology processes of passive RF and microwave print components is given in Tables 3-9.

The price of RF and microwave components falls as the ordered quantity increases. If the quantity is high enough it is possible to adopt automated assembly and test techniques. Also, for high quantities of RF and microwave components, the technology process can be changed, for example, from PCB to hybrid or monolithic technique. Guidelines that provide cost reduction of passive print RF and microwave components are: use the cheapest technology process; use a low cost carrier substrate; keep assembly as simple as possible. Table 4 shows the relative cost of different technology processes.

Figure 2 illustrates the dialog box for different transmission lines, technology processes, and materials. Using this box, a designer can enter the INPUT requirements and the specific application. Also, for a known transmission line (Version 2 or Version 4), its type and physical dimensions should be entered. Analysis of a known transmission line provides OUTPUT with all electrical performances. For an unknown transmission line (Version 1 or Version 3), the known INPUT electrical performance should be entered. In this case, the synthesis provides OUTPUT including type and physical

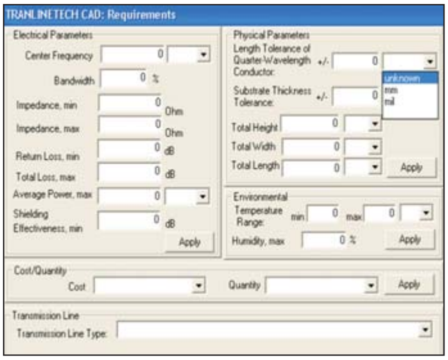

Figure 2 · Dialog boxes section of TRANLINETECH screen.

dimensions of the optimal transmission line. For each type print transmission line we can calculate its electrical properties as the result of analysis or its physical dimensions as the result of synthesis. Also, using the TRANLINETECH, we can optimize the technology process and materials for the print transmission line. For the analysis of the microstrip line, the input parameter ranges are: conductor with to substrate height ratio $0.1 < W/h < 3.0$; h = 5-60 mils; 0.5 mil < W < 180 mil. The output parameters are characteristic impedance Z_0 = 15-120 ohms; effective dielectric constant $1.5 < \varepsilon_{eff} < 20$, loss α, cut-off frequency f_{max}, and maximum power P_{max}. For the synthesis of the microstrip line, the input parameters are: center frequency and frequency range, characteristic impedance range, return loss, total loss, maximum power, cost, technology process, and materials. The output parameters are the physical dimensions of the ML (conductor width, substrate thickness, total height between ground plane and cover).

Substrate materials of an IC should have the following characteristics: low cost, low dielectric loss, low dielectric constant in order to reduce cost and effects of tolerances variation, or high dielectric constant for a smaller size and less radiation loss. Tables 7 and 8 show different substrate and conductor materials which are used for RF and microwave print components.

Technology Processes	Substrate Materials	Conductor Materials
PCB	Plastic	Cu, Ag, Au, Al, TIN
Thick-film	Ceramic, Ferrite, Ceramic/Ferrite	Pastes: P202, PdAg; P-120, Ag; P-401, Pt/Ag; 1130C, Pt/Ag; P-727, Ni; DP714L; QS190, Cu; QP163, Cu; Pd/Au; Pt/Au; Au QG150; Ag 4065.
Thin-film	Ceramic, Sapphire, GaAs, Si, Ferrite, Si/Sapphire, Si/Glass	Au, Cu, Ti/Au, Cr/Ni/Au, TaNi/Ti/Au, Ni/Ni/Au
LTCC	Low Temperature Co-fired Ceramic	Au, Ag, Au/Ag
DBC	Ceramic	Cu (0.005-0.020 in THK)
Monolithic	GaAs, Si	Au, Cu

Table 7 · Substrate materials and conductor materials for different technology processes.

Performance	Substrate Materials							
	Plastic	Ceramic	Low Temperature Co-fired Ceramic	Sapphire	Quartz	Ferrite	GaAs	Si
Dielectric Constant	2.0-10.2	3.0-10.0	5.0-10.0	9.4; 11.6	3.78	10.0-20.0	12.9	11.7
Dielectric Loss Tangent	0.0001-0.010	0.0001-0.005	0.001-0.006	0.0001	0.0001	0.0003-0.010	0.006	0.001-0.010
Thermal Conductivity (W/m-°K)	0.1-10.0	0.5-300.0	0.5-10.0	46.0	1.0	2.0-5.0	54.0	151.0
Thickness (inch)	0.005-0.150	0.005-0.060	0.002-0.020	0.005-0.020	0.003-0.040	0.005-0.50	0.004-0.060	0.005-0.070

Table 8 · Performance of substrate material.

The most contradictory parameters of passive printed RF and microwave components are: cost vs. size, cost vs. loss, cost vs. shielding, loss vs. volume, RF power vs. cost and size. These parameters should be optimized by a tradeoff design. The transmission line integration index of two parameters—loss vs. volume—can be described by [2]:

$$i = \alpha_\Sigma \times V_\Sigma^{\frac{1}{3}}\ (dB \times inch)$$

where α_Σ is the total insertion loss of the print transmission line; V_Σ is the volume of the transmission line, $V_\Sigma = L_\Sigma \times W_\Sigma \times H_\Sigma$, where L_Σ, W_Σ, and H_Σ are total (equivalent) length, width, and height of the transmission line.

Let us consider design aspects of *passive RF and microwave components*. A directional coupler is a reciprocal four-port component, which provides two amplitude outputs when a signal is applied to its input. There exist the following types of directional couplers: ring, branch-line, and coupled-line. Electrical characteristics of directional couplers are: frequency band, insertion loss, coupling, isolation, directivity, matching or return loss, phase balance, bandwidth, and power. Bandwidth of the coupled-line directional coupler can be enlarged by increasing the number of sections. Bandwidth of the branch coupler can be enlarged by increasing the number of branches, which causes an increase in physical size. Also, couplers with more than four branches are difficult in microstrip because the end branches require impedances at the upper limits of practical implementation. In addition, an increase in impedance of end sections and a corresponding decrease of the conductor width lead to an increase in loss.

Therefore, the tradeoff design of the broadband directional couplers should provide the optimal solution for the following contradictory parameters: bandwidth vs. size, bandwidth vs. technology tolerances and cost, and bandwidth vs. loss. The microstrip coupled-line directional coupler has a low directivity (10 to 15 dB), which drops even further as the coupling becomes weaker. The tradeoff design with contradictory directivity vs. coupling requires the modifications of the conventional coupled-line directional couplers [3].

A reciprocal *divider* can provide an equal or unequal power split between two or more channels. Because of their reciprocity, these networks may also be employed to combine a number of oscillators or amplifiers at a single port. Electrical characteristics of a power divider are: frequency range, number of channels, insertion loss, isolation between channels, matching or return loss, power division, bandwidth, amplitude balance, phase balance, and maximum handling power. In dividers which use directional couplers, the power split coefficient is proportional to the square of the ratio of admittances of coupler segments. A decrease in admittance and a corresponding decrease in the width of the conductor lead to increased losses. In this case, unequal losses take place on different segments of a directional coupler which results in deviation from the specified power split, mismatching, and decreased isolation. In multi-section power dividers, as the number of sections is increased, bandwidth and isolation substantially increase, although insertion losses become higher.

RF and microwave *filters* suppress unwanted signals and separate signals of different frequencies. Electrical specifications of filters are: cutoff frequency, input/output impedance, rejection, ripples in passband, pass band attenuation, order, stop band attenuation, second/third-harmonic attenuation, *VSWR,* frequency response, phase response, group-delay, impedance of resonators, guide wavelength, power, cutoff frequency, frequency range, and passband. The typical band pass filter (BPF) tradeoff design includes the choice of the filter transfer function. Butterworth function filters have no ripples—insertion loss is flat in the frequency band and rises monotonically with frequency. Chebyshev function filters provide much faster rise of the insertion loss with frequency for a maximum specified passband ripple. Since increased ripples result in better selectivity, this approximation offers a compromise between passband ripple and selectivity.

Most coupled-line BPFs involve gaps between coupled lines, which can be just several thousandths of an inch wide. These gaps, as well as resonator width and substrate dielectric performances, are critical for the electrical performance of the filter. For example, as the bandwidth is increased, the gaps become smaller, which may increase production difficulties and the effect of the tolerances. Tighter tolerances are possible at a higher cost and a very low yield. For narrow bandwidths, a weaker coupling in the larger gap between the coupled lines is required, which leads to an increased difficulty in controlling the required coupling. If we increase the BPF selectivity then the number of elements, and hence the passband loss, increases. A highly selective, narrowband, low loss BPF has significant physical dimensions because the *Q*-factor of a resonator is proportional to its size. The integration quality of the BPF is characterized by the following contradictory parameters: volume, minimum dissipated losses, bandwidth, and number of sections. The relationship between these parameters using the BPF integration index is described in [3].

For the conventional print ed stepped-impedance LPF, the main problem is achieving a minimum loss with a small size. The result of LPF tradeoff design is a combination of series small high-*Q* microstrip inductors and shunt capacitors [3, 12]. This combination allows a very large impedance ratio, and therefore a very good stopband performance, in addition to small size.

RF and microwave *baluns* are the key passive components of double-balanced mixers, push-pull amplifiers, antenna-feed networks, etc. A balun uses combinations of the following different print lines: ML (unbalanced) to SLL (balanced), CPW (unbalanced) to SLL, ML to CS (balanced), etc. The tradeoffs of a balun are bandwidth vs. size, bandwidth vs. loss, and bandwidth vs. reflection coefficients.

RF and microwave *phase shifters* have many applications in various systems. Electrical specifications of a phase shifter are: phase shifter type, phase shift, phase shift error, loss, VSWR, impedance of segments, input/output impedance, guide wavelength, power, frequency range, and bandwidth. Multi-bit switched line phase shifters [3] can be used to vary the phase shift up to 3600. Digital phase shifters provide a discrete set of phase states that are controlled by two-state "phase bits." The number of binary weighted phase shifting "bits" can be cascaded to realize a variable phase shifter covering the desired range. By using proper combination of on/off states, one can implement any discrete number of phase states between 0 and 360 degrees. To minimize the phase quantization error, one should increase the number of bits, and hence the number of phase shifters. A greater number of bits causes higher complexity, higher RF loss, and lower tolerance interval of the side-lobe level for the antenna array pattern.

Ferrite isolators and circulators are *N*-port nonreciprocal devices providing one-way sequential transmission of power between their ports. Electrical specifications of an isolator/circulator are: isolation, loss, VSWR, impedance of segments, mode operation, saturation magnetization, effective permeability, direction of circulation, magnetic field strength,

Print Component	Layer Material			QTY of Layers	
	metal	resistive	dielectric	single	two or more
Directional Coupler	+	+	+ (Coupled Line with Strong Coupling)	+	+ (Coupled Line with Strong Coupling)
Divider/Combiner	+	+ (Wilkinson Divider)	-	+	-
Filter	+	-	+ (with Suspended Substrate)	+	+ (with Suspended Substrate)
Balun	+	-	+	+	+
Phase Shifter	+	-	-	+	+
Ferrite Isolator/Circulator	+	+ (Isolator)	-	+	+ [3]
Duplexer	+	-	-	+	-

Table 9 · Layer structure for different RF and microwave print components.

input/output impedance, guide wavelength, power, frequency range, and bandwidth. Most electrical characteristics are functions of circuit geometry, type of ferrite, and the strength of the biasing magnetic field.

RF and microwave *duplexers* connecting a single antenna to the transceiver direct the transmitter energy to the single antenna and the energy received by the antenna to the receiver. A duplexer involves a ferrite circulator or a transmit/receive switch. The most contradictory parameters of a duplexer are: loss vs. isolation, power, size, and cost; isolation vs. frequency band; size vs. power, cost, and bandwidth [7].

High-density integration of RF and microwave integrated circuits requires integration of a large number of passive components. The *multilayer circuit board* provides integration of RF/microwave and digital circuitry within a single compact assembly and decreases the overall physical area. The other reason for employing multilayer configuration is that several passive RF and microwave components (for example, baluns and tight coupling directional couplers) are difficult to realize in a single-layer planar structure. Interconnections in a multilayer circuit board include vertical vias. Multilayer construction can be realized using LTCC or PCB technology. The multilayer PCB is manufactured with thermoplastic substrates and thin (~2 mil) prepreg between layers. Table 9 shows layer structures for different RF and microwave print components.

Higher frequency communication standards require a tighter performance of the passive components due to a relatively stronger effect of parasitics at these frequencies. For RF and microwave components, printed transmission lines generally offer the smallest sizes and the easiest fabrication. However, it does not offer the highest electrical performance. Sometimes an RF component prototype with a previously selected transmission line does not satisfy requirements. In this case, the transmission line and the chosen passive component should be modified (see the 8th step of the flow chart, Fig. 1a). Besides single print transmission lines, implementation of double and triple lines is also possible [2, 3, 4]. Combinations of different print transmission lines are necessary for some RF and microwave components, for example, baluns, multilayer structures, and antenna-feed networks. Also, the ground structure of a microstrip line can be modified to improve the electrical performance and reduce the size of print components. Microstrip components with defected ground (DGP) are low-pass filters [8-10], dividers/combiners, directional couplers [11]. Novel microstrip RF and microwave components with ground plane aperture (GPA) (filters, dividers/combiners, phase shifters, directional couplers) and components with ground plane lossy aperture (GPLA) (resistors, terminations, and attenuators) were discussed in [12].

The main functions of the *packages* of RF and microwave IC are mechanical support, protection from environment, and thermal stabilization. The total housing height should be greater for higher average power capability and loss but this leads to an increase in overall physical dimensions. There are different types of packages: metal, ceramic, plastic, and multilayer [3, 4]. The most contradictory characteristics of a package are shielding vs. cost and size, size vs. loss. Non-hermetic plastic packages have been widely used because of their low manufacturing cost. The expensive metal housings provide excellent electromagnetic shielding, thermal dissipation, and mechanical reliability. Dimensions of a metal housing should be selected so that the waveguide modes are below cutoff. This is a typical conflict of interest between integrated circuit loss and housing size. A ceramic package provides moderate cost and low weight. This package can be made hermetic using, for example, a metalized alumina substrate. The most widely used ceramic packages are implemented using LTCC technology. The problems of the ceramic packages are the interconnect line loss, the parasitic effects, and the mechanical stress in the multilayer structure due to the environment.

Most aspects of the tradeoff design process described in this paper are summarized in Figure 3. It shows ways to optimize passive RF and microwave components, technology processes, transmission lines, and integrated packages.

References

1. N. Pulsford, "Passive Integration Technology: Targeting Small Accurate RF Parts," *RF Design,* November 2002, pp. 40-48.

2. L. G. Maloratsky, "Setting Strategies for Transmission Lines," *Microwaves & RF,* Part 1, September 2008, pp.100-112, Part 2, October 2008, pp. 84-86.

3. L. G. Maloratsky, *Passive RF &*

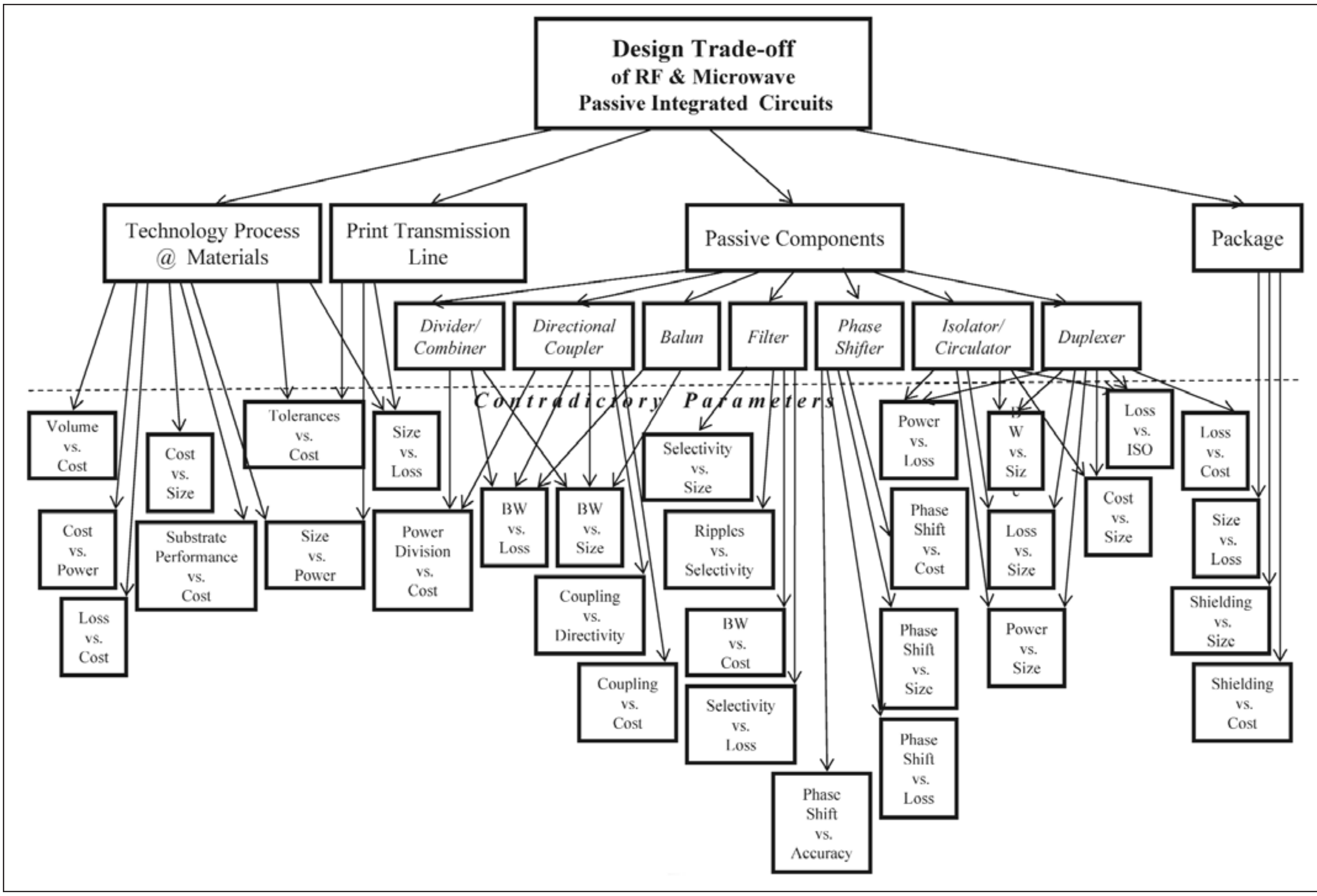

Figure 3 · Summary of the design tradeoff process.

Microwave Integrated Circuits, Elsevier, 2004.

4. L. G. Maloratsky, "Combinations of Various Print Transmission Lines: Design and Applications," *Microwave Journal.*

5. C. Reynolds, "A Review of High Frequency Passive Component Technologies (Thin-Film, Thick-Film, Discrete & PMC) for RF Design Applications," AVX Technical Information, http://www.avx.com/docs/techinfo/areview.pdf

6. S. Kayali, et. al., "GaAs MMIC Reliability Assurance Guideline for Space Applications," NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, December 1996.

7. L. G. Maloratsky, "Transceiver Duplexer Design Considerations," *Microwave Journal,* October 2008, pp. 68-86.

8. Jong-Sik Lim, et al., "A New Type of Low Pass Filter with Defected Ground Structure," *IEICE Transactions on Electronics,* 2005 E88-C (1), pp. 135-138.

9. J. Chen, et al., "Lowpass Filter Design of Hilbert Curve Ring Defected Ground Structure," *Progress in Electromagnetic Research, PIER 70,* 2007, pp. 269-280.

10. R. Zhang, et al., "A Novel Lowpass Microstrip Filter Using Metal-Loaded Slots in the Ground Plane," *IEEE-MTT-S Digest,* 2004, pp. 1311-1314.

11. R. Sharma, et al., "Design of a Novel 3-dB Microstrip Backward Wave Coupler Using Defected Ground Structure," *Progress in Electromagnetics Research, PIER 65,* 2006, pp. 261-273.

12. L. G. Maloratsky, "Microstrip Circuits with Modified Ground Plane," *High Frequency Electronics,* December 2009, pp. 38-47.

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