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Using Modified Microstrip Lines to Improve Circuit Performance

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This article is a thorough review of the ways a microstrip line can be modified for space savings, a simpler layout, or enhanced performance

The numerous modifications of microstrip lines are considered in this article. Modified microstrip lines are used to achieve performance goals that acannot be obtained using simple, uniform structures. They are categorized according to their physical dimensions, structures, substrate materials, ground plane configurations, and conductor shapes.

The development history and possible modifications of microstrip line (ML) are illustrated in Figure 1. The historical base of ML was a *coaxial line*, which provides a dominant mode with zero cutoff frequency, low loss, and a very wide bandwidth. However, this line makes it difficult and expensive to create passive and active transmission line based components and devices. The first attempt to overcome this disadvantage was the rectangular coaxial line with strip center conductor. The next step was removing the side walls and extending the top and bottom ground planes, with the result called the *stripline* (SL). The development of planar transmission lines started in the 1950s, when Barret and Barnes

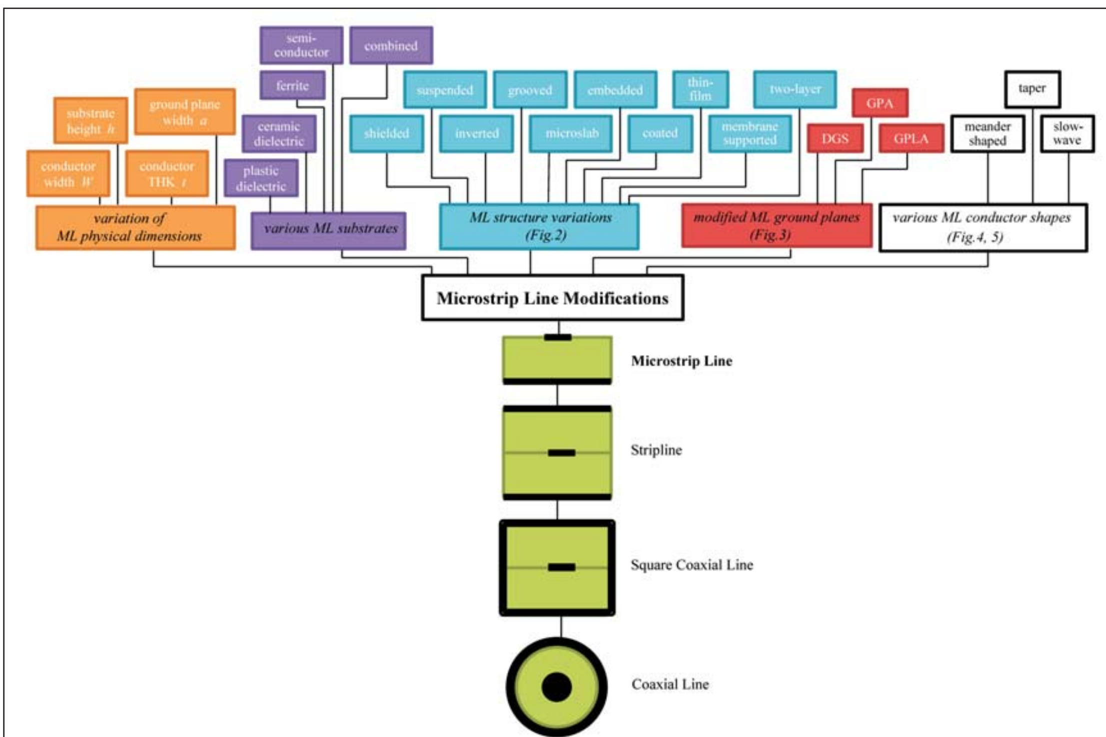

Figure 1 · Possible modifications of microstrip line

invented the symmetrical SL [1, 2]. To support the center conductor, it was filled with dielectric material.

The next modification of transmission line involved removing the top ground plane and the top dielectric substrate. That modified structure was named the *microstrip line*. The ML is transmission line geometry with a single conductor trace on one side of the substrate and a single ground plane on the other side. The developments of ML are summarized in [3, 4]. The evaluation of MLs began in 1952 when the microstrip line was introduced [5-8]. During the past 40 years, ML has played a key role in the growth of new RF and microwave applications. Right now, ML is more popular than SL, but SL is still essential for RF and microwave components having high-Q, low dispersion, and wide frequency range. Also, various printed transmission lines are in use [9-11].

For RF and microwave devices, the general microstrip line (Fig. 2a) offers the smallest sizes and the easiest fabrication. Since ML is an open structure, it has a major fabrication advantage over SL. However, modifications of the general ML are often necessary due to certain inherent disadvantages and limitations. The main disadvantages of the general ML are low Q-factor, radiation, electromagnetic interference, dispersion, and environmental problems. The general ML is open to the air, while in practice it is desirable to have circuits covered to protect them from the environment, as well as to prevent radiation and electromagnetic interference (EMI). For the general ML, attenuation losses, size, and power handling are contradictory, and a trade-off among them must be reached. Also, there are the following limitations of this line: moderate impedance range (15-120 ohm), frequency range (below 60 GHz), power handling, unbalanced input/output signals, and difficulties of the assembly of shunt elements.

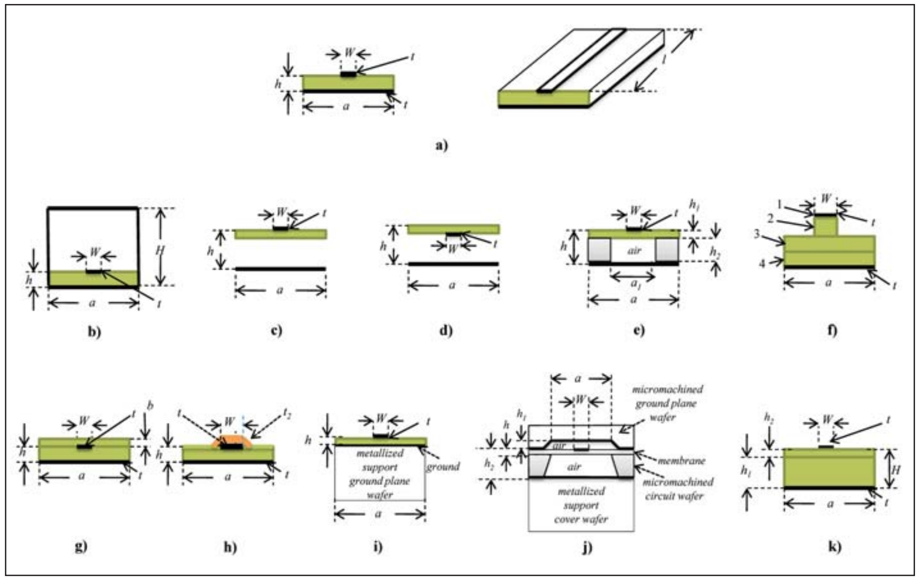

Figure 2. · Various microstrip line configurations, as described in the text.

There are numerous modifications of the general ML that can be used as alternative structures for RF and microwave integrated circuits. The realization of modified MLs can be divided into four categories: variations in physical dimensions, structure variations, different substrate materials, modifications of the ground plane, and different conductor shapes.

1. Physical Dimensions Variation

MLs can be modified by varying physical dimensions *W, h, t, a,* and *l* (see Fig. 2a) [9]. For all ML circuit considerations, a basic approach involves starting with particular ranges of the dimension ratios required to achieve desired characteristic impedance. The impedance of ML is primarily determined by the ratio W/h. The strip width W should be minimized in order to decrease 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. In some practical components (transformer, baluns), the ML is modified by varying conductor width. The positive effects of decreasing ML substrate height h are compact circuits and ease of integration. A decrease in substrate thickness h must be accompanied by a narrowing of conductor width W in order to maintain constant characteristic impedance Z_0. Also, for smaller W and h, fabrication tolerances become more severe. The thin substrates required make for very delicate in-process handling. Such processing conditions can result in poor fabrication yields. At higher frequencies, even thinner substrates must be used. At 60 GHz, a typical substrate thickness h must not exceed 0.008 inches. The width a of the ML ground plane should be at least four-five times the conductor width W to decrease radiation loss. In some applications (baluns, tapers), the width of the ML ground plane a can decrease gradually over the length of transmission line l (to minimize reflections) until it becomes equal to that of the upper line W. In this fashion, the quasi-TEM field of the ML is converted into a pure TEM field of broadside strips [10].

For low-loss RF and microwave components the conductor thickness (THK) t of ML should be greater than approximately three to five times the skin depth δ_c to minimize conductor loss. For the high-loss microstrip resistors and attenuators, conductor THK should be less than δ_c. High power microstrip components require THK of the conductor and the ground plane to be much greater than δ_c. Materials for the conductor and the ground plane of ML depend on technology process and applications. Microstrip resistors and attenuators are produced by depositing thin films of lossy metal on the substrate base. Nichrome and tantalum are widely used due to their good stability and low TCR. High-power microstrip components can be implemented by direct bond copper (DBC) process including directly bonding the copper sheet to the ceramic or ferrite substrate, after which a pattern is formed thereon by masking and etching. The use of a 10-mil-thick solid copper foil provides lateral as well as vertical heat flow from ML. Printed circuit technology (PCB) uses the copper cladding (with THK as 0.7-2.8 mil) on a substrate. Two basic types of copper are available for microstrip PCB: electrodeposited and rolled annealed [9]. The thick-film technology uses special conductive paste (silver, gold, palladium-gold, and so forth) for ML conductors. Thin-film technology involves sputtering a metal (chromium, nickel, and so forth) that has good adhesive performance with the substrate to form a thin (approximately 100-200 Å) adhesive layer. The next step is sputtering a layer of Au having a similar THK. Then, a high-conductivity metal is electroplated on top to provide the necessary THK of metal film of three to five skin depths.

2. Microstrip Line Structure

Variation. Cross sections of the commonly used types of MLs for MIC are shown in Figure 2. These include general ML (Fig. 2a) and the following structure variations: shielded ML (Fig. 2b), suspended ML (Fig. 2c), inverted ML (Fig. 2d), grooved ML (Fig. 2e), microslab (Fig. 2f), embedded ML (Fig. 2g), coated ML (Fig. 2h), thin-film ML (Fig. 2i), membrane supported ML (Fig. 2j), and two-layer ML (Fig. 2k). Each of these types offers a certain advantageous feature with respect to other types.

Protection of ML from environmental influences as well as prevention of radiation and electromagnetic interference can be realized by the use of shielded ML (Fig. 2b). The main purposes of the metal package of the ML are to provide electric shielding, mechanical strength, germetization, and heat sinking in the case of high power application. The width of the shielded ML a is equal to the sum of the conductor width W and the EM area ($3W$ - $5W$) around the conductor. In shielded ML, the total height H is equal to $5h$ - $7h$ (see Fig. 2b) [9,11]. When H is greater than that, the enclosure effects are negligible. Fitting a microstrip circuit into a housing may be looked upon as a dielectrically loaded cavity resonator with physical dimensions selected in such a way that the waveguide modes are below cutoff [9].

Suspended (Fig. 2,c) and inverted (Fig. 2,d) MLs utilize an air gap under the substrate, which considerably decreases the dispersion of the line parameters and reduces losses because most electromagnetic field is concentrated in the air gap area. The inverted line offers the advantage of lower ohmic losses, because RF current is concentrated in the high-conductivity copper conductors of PCB. Suspended and inverted lines provide a higher Q-factor (Q = 500-1500) than the general ML (Q = 250). Dispersion increases with increasing substrate permittivity and reducing the strip width. The air gap reduces the effective dielectric constant of the medium, which in turn increases physical dimensions of components. Another effect of lower effective dielectric constant is an increased width of the strip conductor. This means that the dimensional tolerances can be relaxed, which is very important at higher frequencies, including millimeter-wave frequencies. Suspended and inverted MLs allow a wider range of achievable impedances. These lines are among the principal transmission media used in the upper microwave and lower millimeter-wave bands. The grooved ML (GML) (Fig. 2e) is a variation of the suspended ML. The GML provides better solution for construction and assembly [12]. Grooves can be carved in the carrier substrate (Si or GaAs) to create less dispersion as compared with the general ML (Fig. 2a). Dielectric and conductor losses of the GML can be reduced as the groove width is increased. The GML is used in MMIC technology.

Multilayer microstrip techniques are now widely used in order to reduce circuit size and realize more complicated circuits. In multilayer constructions, an additional dielectric, ferrite or semiconductor substrate can be used. Examples of multilayer microstrip circuits are 3 dB Lange coupler, non-reciprocal ferrite devices, baluns, etc. The microslab (strip-ridge structure) (Fig. 2f) [13, 14] is a modification of the ML. It consists of a conductor strip (1) on top of the dielectric strip (2) placed onto the double dielectric layer. Dielectric permittivities of the dielectric strip (2) and the bottom dielectric layer (4) are lower than that of the second dielectric layer (3). At low frequencies, the electromagnetic mode is somewhat similar to the quasi-TEM. At higher frequencies, the greater part of the electromagnetic field is in the second dielectric layer (3). Therefore, this construction looks like a quasi-planar waveguide that proves useful for many interesting applications in millimeter- and submillimeter-wave integrated circuits. The microslab combines the wideband feature of ML and the low loss characteristic of planar dielectric waveguides. The line loss in the microslab was measured at 94 GHz [4] and was found to be only 0.4 dB/inch, compared with a loss of 2.5 dB/inch at that frequency for ML, an improvement of almost six to one.

Usually, the microstrip circuit should be covered in a solder mask, a thin layer of epoxy, or prepreg material, creating embedded (Fig. 2g) and coated (Fig. 2h) ML. The coating materials can lower the impedance by up to a few ohms (depending on the type and thickness of the coating material). In the embedded (or buried) ML, the microstrip conductor is embedded in a dielectric. In this structure, the dielectric is made up of two dielectric layers. As a rule, signals passing through an embedded ML run approximately 20% slower than a standard ML. The impedance of an embedded ML is somewhat more controllable, because the dielec-

Structure	Advantages	Disadvantages
General ML (Fig. 2,a)	Small size, low cost, easiest fabrication	low Q-factor
Shielded ML (Fig. 2,b)	Shielding, germetization	high cost
Suspended ML (Fig. 2,c)	Low dispersion, low loss, wider impedance range	low integration, manufacture difficulties
Inverted ML (Fig. 2,d)	Low dispersion, low loss, wider impedance range	low integration, manufacture difficulties
Grooved ML (Fig. 2,e)	Low dispersion, low loss, wider impedance range, easy construction and assembly	low integration, manufacture difficulties
Microslab (Fig. 2,f)	Wide band (up to mm waves)	high cost for low QTY
Embedded ML (Fig. 2,g)	Protection from environmental, inclusion of second signal layer, useful for multilayer board	radiated emission, slower signal propagation
Coated ML (Fig. 2,h)	Protection from environmental, inclusion of	radiated emission, slower signal propagation
Thin-film ML (Fig. 2,i)	second signal layer, smallest size, terahertz operation	low Q-factor
Membrane supported ML (Fig. 2,j)	High frequency application, lowest loss, high characteristic impedance, low dispersion	high cost for low QTY
Two-layer ML (Fig. 2,k)	Possibility of electrically-tunable devices	low Q-factor

Table 1 · Summary of performances for the different microstrip lines shown in Figure 2.

tric constant is the same above and below the transmission line. The extra layer of dielectric material has more effect on the effective dielectric constant of a line with narrow strips.

The thin-film ML (TFML) (Fig. 2i) [15] is the miniaturized version of the general ML. A signal conductor, a dielectric, and a ground conductor are located on top of the low-resistivity carrier substrate (Si or GaAs). The fields are concentrated in the dielectric layer and the ground metallization provides shielding against the semiconductor substrate. Therefore, low resistivity carrier substrates can be used without deteriorating microwave performance. The Si or GaAs substrate provides the support as well as the semiconductor medium for the active device. The typical benzocyclobutene (BCB) and polyimide substrate thicknesses are in the range of 1-25 μm. For BCB and polyimide materials, relative permittivity is usually 2.65 and 3.2, respectively. A disadvantage of a TFML is that the permittivity is considerably lower than GaAs or Si, and, therefore, the physical lengths are longer. For general MLs, height and width of the signal conductor are in the range of hundreds of microns. For TFMLs, these values are around 10 μm, on the order of magnitude of metallization thickness, which increases the frequency range of quasi-TEM operation well into the Terahertz region. Small dimensions (very narrow width and thin THK) increase conductor loss. Scaling down the dimensions yields excellent dispersion properties and low radiation at the expense of higher conductor loss. Attenuation levels are in the range of 5-10 dB/mm at 1 THz. Given the short line lengths in monolithic structures, this is acceptable. TFMLs are used in circuit for which miniaturization is more important than transmission line loss. TFMLs have been widely employed to fabricate various high-density passive and active components in multichip modules, which are used in Si-based monolithic microwave and mm-wave integrated circuits. Properties of TFML properties do not depend on the quality of the semiconductor substrate. In part because of this, TFML covers a wider impedance range. Between TFML and the general microstrip configuration (Fig. 2a) there exist evident differences in geometrical dimensions, which can cause significant discrepancies in the electrical behaviors. TFML is only appropriate for low-power systems.

The membrane supported ML (Fig. 2j) is formed by removing the semiconductor substrate and suspending a ML on a thin (1.4 μm) dielectric membrane [16]. The conducting strip is not positioned symmetrically between the two ground planes. The metalized cavity with the depth of h_1, which is smaller than the micromachined circuit wafer thickness h_2, provides the function of ML ground plane. The metalized support cover wafer provides low radiation loss of the membrane supported ML. Because the microstrip metal trace is supported by a low-dielectric constant membrane, the line is very close to being homogeneous. This results in the propagation of nearly TEM modes, a virtually negligible dielectric loss, and an extremely wide single-mode propagation bandwidth. The characteristic impedance of this line is high (50-160 ohm) because the conductor of ML is suspended in the air gap area. A nearly pure TEM mode is propagated in this structure. This micromachined version of ML is extensively used in DC to submillimeter-wave frequency range. For this type of structure, dielectric loss is eliminated due to the air dielectric. In this line, the exhibited conductor loss and dispersion are considerably lower than in other ML modifications.

Structure	Impedance Range (ohms)	*Q*-factor
General ML (Fig. 2,a)	15 - 120	250
Shielded ML (Fig. 2,b)	15 - 120	250
Suspended ML (Fig. 2,c)	40 - 150	500 - 1500
Inverted ML (Fig. 2,d)	25 - 130	500 - 1500
Grooved ML (Fig. 2,e)	30 - 140	
Embedded ML (Fig. 2,g)	15 - 100	
Coated ML (Fig. 2,h)	17 - 110	
Membrane supported ML (Fig. 2,j)	50 - 160	400 - 500

Table 2 · Impedance range and *Q*-factor of different microstrip lines.

The two-layer ML (Fig. 2k) consists of a dielectric substrate, a ferroelectric thin-film layer, a conductor, and a ground plane. The dielectric properties and the thickness of the ferroelectric thin film greatly influence the variation of frequency and phase, and the overall insertion loss of the circuit [17]. Frequency and phase agility for ferroelectric tunable devices is achieved using the perpendicular dc electric-field (between the top conductor and the ground plane) which changes the effective dielectric constant of this structure. The typical physical dimensions of this line are: dielectric substrate THK h_1 = 300 µm, ferroelectric film THK h_2 = 300-2000 nm, conductor and ground plane thickness t = 2 µm.

Tables 1 and 2 show performances of different ML structures. The tradeoff design of the ML should provide the optimal decision between the following contradictory parameters: size vs. loss, loss vs. cost, bandwidth vs. size, and bandwidth vs. loss.

3. Substrate Materials

The basic ML parameters, i.e., characteristic impedance, phase velocity, effective dielectric constant, losses, and power-handling capability, depend on properties of the substrate material. Historically, during the 1950s-1960s, the most miniature RF and microwave elements and devices were based on ML with plastic dielectric substrates. The PCB technology, which is still very popular, was based on the use of copper-laminated plastic substrates. These organic-type plastic materials feature low dielectric constants, have low loss, are easy to machine, and are low in cost. Later, when new technology processes, such as hybrid microwave integrated circuits (HMIC) and monolithic microwave integrated circuits (MMIC) appeared, the variety of ML substrate materials was widened. The low-temperature-cofired-ceramic (LTCC) technology [18] is based on multiple stacked layers of ceramic materials. The dielectric material most commonly used for thick-film technology is Al_2O_3 (96%). For thin-film technology, the typical substrate materials are Al_2O_3 (99.6%) or ferrites (for nonreciprocal devices). The direct bond copper (DBC) process [5] is used for directly bonding the copper sheet to the ceramic or ferrite substrate in order to realize high-power devices. Therefore substrates with excellent thermal conductivities, such as aluminum nitride (AlN) and beryllium oxide (BeO), are used. MMICs are fabricated on semi-insulating substrates, such as GaAs, Si, InP, and composite semiconductor materials, such as silicon carbide (SiC) and silicon germanium (SiGe). One integration option is the quasi-monolithic technology which uses semiconductor layers on the dielectric substrate (e.g., silicon-on-sapphire combination). In the glass microwave integrated circuits (GMIC), epitaxial Si is used for active devices, and low-loss glass dielectric is used to fabricate passive elements. The parameters of ML depend on substrate dielectric constant ε and effective dielectric constant ε_{eff} [9, 11]. Electromagnetic fields in ML exist partly in the air above the substrate and partly within the substrate itself. Therefore, the effective dielectric constant ε_{eff} of the ML can be justly expected to be greater than ε of air (ε = 1) and less than that of the substrate material.

4. ML with Modified Ground Plane

The most popular ML includes a conductor trace on one side of a substrate and a single ground plane on the other side (Fig. 2a). However, the ground plane structure can be modified to improve electrical performance and reduce the size of the microstrip circuit. Modifications of the ML ground plane can be divided into the following categories: physical dimensions variance, defected ground plane structure (DGS), ground plane aperture (GPA), and ground plane lossy aperture (GPLA). In recent years, there have been several new designs of microstrip circuits with DGS [19-28], etc. MLs with a DGS have much higher impedance and an increased slow-wave factor as compared to conventional transmission lines. A DGS is attractive as it enables unwanted frequency rejection and circuit size reduction. DGS is a new type of microstrip design that exhibits well-defined stop and pass bands in the transmission characteristics, and as such it finds many applications in microwave printed circuits: filters, dividers, amplifiers, oscillators, switches, directional couplers, antennas, etc. A DGS is realized by etching a defective pattern in the ground plane, which disturbs the shield current distribution. This disturbance can change the characteristics of a transmission line, such as equivalent capacitance or inductance, to obtain the slow-wave effect and the band-stop property. A DGS applied to a ML causes the resonant character of the circuit with a resonant frequency controllable by changing the shape and the size of the slot. Various shapes of a DGS cells have appeared in literature [19-28], etc. Figure 2 shows several resonant structures that may be used. The basic element of a DGS is a resonant gap or slot in the ground surface (Fig. 3a), placed directly under the transmission line and aligned for efficient coupling to the line. The dumbbell-shaped DGS (Fig. 3b) includes two wide defected areas connected by a narrow slot. The loaded Q-factor of the U-shaped structure Figure 3c increases as distance s decreases. Figure 3d represents the DGS unit composed of two U-shaped slots connected by the transverse slot. This DGS section can provide cutoff frequency and attenuation pole without any periodicity, unlike other DGS. The equivalent circuit of the DGS can be represented by a parallel LC resonant circuit in series with the ML. The transverse slot in the DGS increases the effective capacitance, while the U-shaped slots attached to the transverse slot increase the effective inductance of the ML. This combination of DGS elements and MLs yields sharp resonances at microwave frequencies which can be controlled by changing shape and size of a DGS circuitry. When a DGS cell is added to a ML, it causes a modification of resonant characteristics of the transmission line, with resonant frequency that can be also controlled by changing shape and size of the DGS slot. Microwave Photonic Bandgap (PBG) structures are conventionally realized by cascading periodic distributive elements. In ML circuits, such PBG properties can be obtained by placing periodic perforated DGS sections on the ground plane along the direction of propagation. The etched ground plane must be far enough from any metal plate, which causes packaging problems. The packaging problems are with space, cooling, mechanical strength and radiation from the ground plane. Also, there is a technological problem with etching of both sides of the substrate.

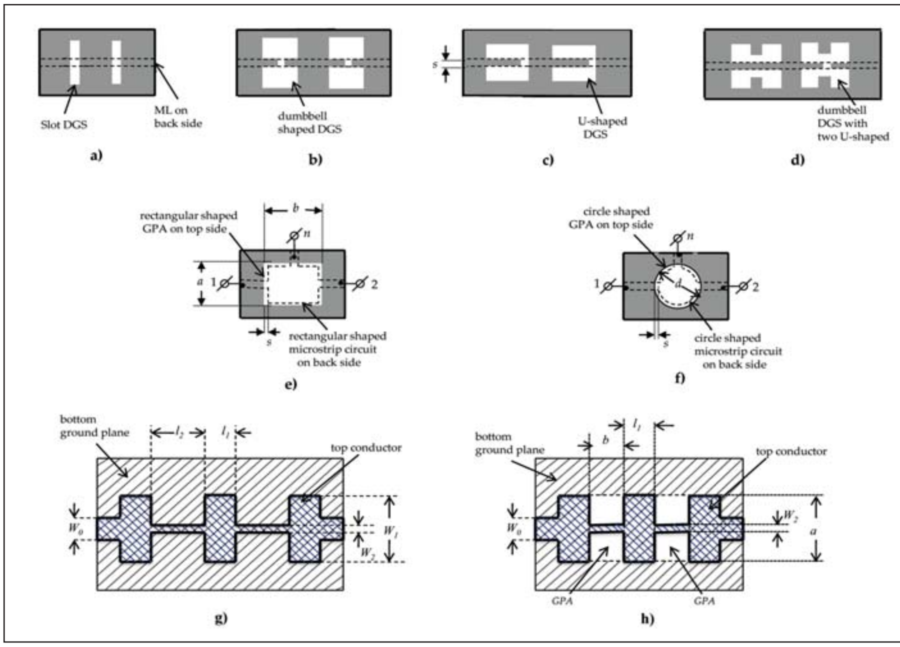

Figure 3 · Ground plane modifications.

ML with GPA and GPLA was described in [29]. A GPA can be rectangular (or square) (Fig. 3e), circular (Fig. 3f), depending on the structure of the microstrip circuit. Compared to a DGS, a GPA has a simple structure and a potentially great applicability to the design of microwave circuits. The GPA can provide reduction in size, strong magnetic coupling between coupled lines, higher impedance, less parasitic capacitance between microstrip conductor and ground plane, and isolation effect between patch antennas. The GPA is formed by removing the ground plane below the microstrip circuit or between patch antennas. The use of the GPA has interesting applications for inductors, transitions between different transmission lines, filters, dividers/combiners, phase shifters, directional couplers, baluns, etc. The conventional stepped-impedance LPF structure is presented in Figure 3g. A short section (length l_2, width W_2) of a high impedance ML can approximate a series inductance. A short section (length l_1, width W_1) of a low-impedance ML can approximate a shunt capacitance. The layout of a stepped-impedance LPF with modified ML realized on a combination of traditional ML and ML with a GPA is shown in Figure 3h. This design uses series high impedance inductive elements based on the ML with the GPA and low impedance shunt microstrip capacitive elements. This combination allows a very large impedance ratio and, therefore, very good stopband performance, in addition to small size as compared with the conventional LPF. Changing the width of the narrow line, W_2, and the wide line, W_1, one can change slow-wave factor. The lengths of the GPA ML sections in the LPF (Fig. 3h) are reduced significantly (by approximately 20%) from those of the narrow ML sections in the conventional LPF (Fig. 3g) due to the significant slow-wave effect of the GPA ML. The LPF with GPA ML shows less size, sharper cutoff performance, and effectively suppression of the spurious passband.

The special GPLA can be used for implementation of planar resistors and attenuators with high surface resistance R_S. In most conventional microstrip designs metal conductor thickness t_c and ground plane THK t_G should be greater than approximately three times the skin depth δ to minimize ML loss. To increase the surface resistance for a termination or an attenuator, the THK of the ground plane in the termination or the attenuator area is chosen to be significantly less than the skin layer THK $t_{GPLA} < \delta$. The GPLA is the GPA with deposited film of lossy metal in the aperture area. This film has low THK of metallization and is chosen to be significantly less than skin depth δ. An alternative is using a low-conductivity material. Nichrome and tantalum are widely used due to their good stability and low TCR. Linear dimensions of both the lumped element termination or attenuator and the GPLA must be less than λ/10. For maximum power dissipation, the distributed planar attenuator with the GPLA can be used. The surface resistance R_S of the GPLA should be chosen as a compromise between the required conductor loss and input matching of the attenuator [9, 29]. For high attenuation values with limited dimensions, the conductor of attenuator or resistor can be given a meander or a spiral line shape. Figure 4a and Figure 4b show the sketch of the planar attenuator with low-conductivity conductor and low-conductivity ground plane.

The recommendations for physical dimensions of GPA and GPLA are the following:

- physical dimensions (length *a*, width *b*, or diameter *d* for circular shape) of GPA should be less than λ/4 (λ is the guide wavelength) to avoid radiation from microstrip circuitry;
- $3W_c$ rule: the space *s* between a microstrip outer conductor (within the GPA area) and perimeter of the GPA should be greater than three conductor widths ($s > 3W_c$) to minimize parasitic capacitance between microstrip circuitry and ground plane;
- THK of the GPLA should be less than the skin layer depth.

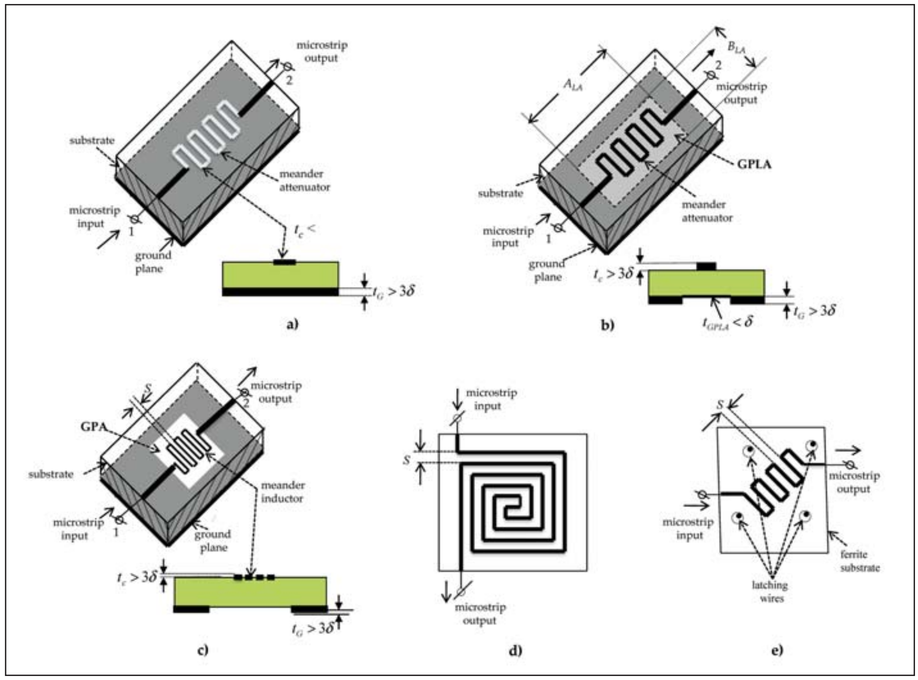

Figure 4 · Meander line configuration choices.

5. ML Conductor Shape

The meander-shaped configuration of a ML provides the most compact area of RF and microwave circuits. Meander lines are used as resistive elements (terminations, attenuators), inductors, delay lines, phase shifters, antennas, etc. Distributed planar attenuator or termination can be realized by using a high-loss uniform ML (Fig. 4a) [9]. This line is implemented by a conductor film with a high surface resistance R_S. To increase the surface resistance, the THK *t* of the conductor is chosen to be significantly less than skin layer THK. An alternative is using a low-conductivity material. The surface resistance R_S should be chosen as a compromise between the required conductor loss and input matching of the attenuator [9]. For high attenuation values with limited dimensions, the conductor of attenuator or the termination can be given a meander (Fig. 4a) or spiral line shape. The distance between the adjacent conductors of such ML must be greater than the doubled width of the conductors. The GPLA [29] can be used for implementation of planar resistors and attenuators with high surface resistance ground plane. To increase the surface resistance for a termination or an attenuator, the THK of the ground plane in the termination or the attenuator area is chosen to be significantly less than the skin layer THK $t < \delta$, while the conductor THK is greater than 3δ (Fig. 4b).

ML lumped inductors can be realized using high impedance meander line (Fig. 4c). In the meander inductor, adjacent conductors have equal and opposite current flows, which reduce the total inductance. Mutual coupling effects are usually small if the spacing is greater than three strip widths. In the meander inductance area, the ground plane should be eliminated to reduce parasitic capacitance between the meander line and ground. Microstrip meander double-spiral delay line (Fig. 4d) consists of a number of closely packed ML segments to achieve high density per square inch of the circuit board, while signal delay is directly proportional to the length of the ML. The parasitic coupling between adjacent sections depends on the separation (S) between the lines and the coupling between the lines and the ground plane. The line width and the substrate thickness are determined by characteristic impedance, and are excluded from design parameters of the meander delay line. The ML meander ferrite shifter is shown in Figure 4e [9]. The meander line consists of tightly coupled quarter-wavelength segments at the center frequency. It provides circularly polarized magnetic field in the ferrite medium and is used for nonreciprocal phase shifters. The space between adjacent segments is approximately equal to substrate THK. The smaller gap between the adjacent meander conductors results in a higher maximum differential phase shift. Two holes (one on either side of the meander line) are drilled in the substrate and latching wires are passed through the holes. Reversing the polarity of the pulse changes the direction of magnetization. In reciprocal phase shifters, the meander line is also used to reduce dimensions. To minimize nonreciprocal effects, the meander conductors must be separated by at least five times the substrate THK and the length of each section is not equal to the quarter wavelength. The reciprocal ferrite phase shifter operates by switching between two orthogonal states of magnetization, one parallel and the other perpendicular to the direction of propagation.

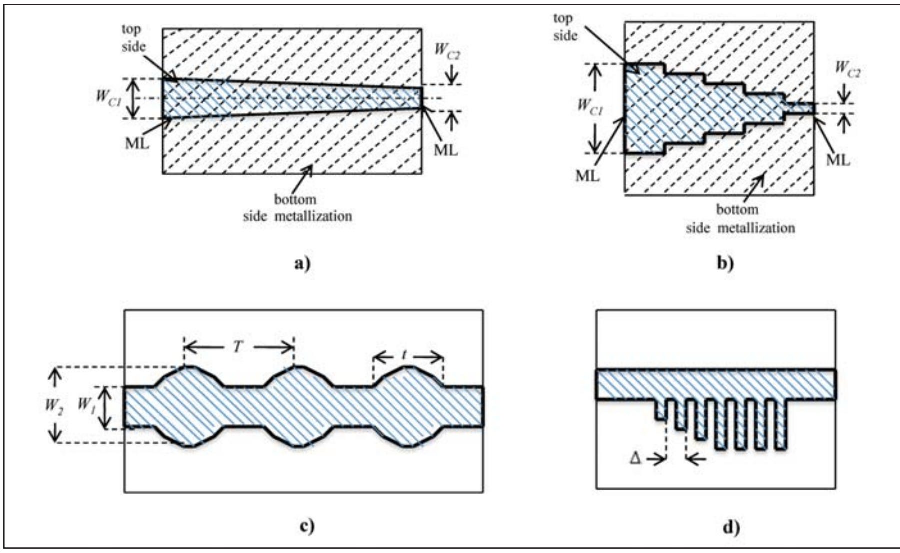

Figure 5. · Tapered, stepped and other line structure modifications.

ML tapers are used mostly in print impedance transformers, low-pass and stop-band filters. To achieve optimum matching between a source and a load one has to give microstrip conductors a specific shape. It is well known that the impedance of a ML varies with conductor width W, substrate THK h, and effective dielectric constant ε_{eff}. The change in impedance by width variation makes matching of different impedances possible. This nonuniform ML exhibits characteristic impedance that varies as a function of the longitudinal coordinate. The design of ML tapers can follow one of the following two general principles: (1) discrete steps (Fig. 5b), each a quarter wavelength long at center frequency; (2) inhomogeneous shapes (Fig. 5a); the advantages are that these tapers have optimum characteristics for a given length, which means that the matching in the passband and the cutoff frequency are ideal and can only be traded off between each other. ML tapers are used as filters, couplers, impedance matching networks, baluns, antenna feed networks, amplifiers, and resonators. Multi-stage microstrip matching circuits have been utilized to obtain minimal reflection loss over a specified frequency range of operation of a device. The tapered stepped ML (Fig. 5b) is divided into five sections. This transformer is used to match unequal characteristic impedances in a wide frequency range. The change of widths of the steps is small, therefore the step discontinuities can be neglected. In the multi-stage transformer with incremental step change in impedance, as the number of sections decreases, the step changes in characteristic impedance between adjacent sections become smaller. Broadband matching condition can be achieved with Chebyshev synthesis techniques. Compensation of a step discontinuity can be implemented using appropriate continuous ML tapers. The following are the basic taper styles of the inhomogeneous shapes: exponential, linear constant, tangential, exponential-constant, parabolic, step-constant, linear, and broken-linear. By changing the taper style, we can obtain different passband characteristics and matching. The width tapering can be implemented for both conductor and ground plane, for ground plane only, or for conductor only. The larger the length of the tapered area, the lower the frequency for a particular return loss.

Slow-wave phenomena take place in periodic microstrip structures. Various kinds of periodic MLs are investigated for applications like filters and delay lines. Figure 5c illustrates the periodic ML width sinusoidal modulated conductor [30, 31]. The characteristic impedance varies between Z_{max} and Z_{min} [$(Z_{max} \times Z_{min})^{1/2}$ = 50 ohm] according to the variation of the width of the ML conductor (from W_1 to W_2). When the loading factor t/T is varied from 1.0 to 0.6, attenuation and bandwidth of the second stopband increase, but the first stopband is only slightly affected. Figure 5d shows the ML comb-type slow-wave structure [9]. The center conductor represents a "comb" of open-circuited stubs. The stubs gradually increase in length from 0 to 0.125λ_0. The step of comb-type structure is $\Delta \leq h/3$ and the width of each stub is equal to the gap between the stubs.

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