From December 2009 *High Frequency Electronics*

Microstrip Circuits with a Modified Ground Plane

By Leo G. Maloratsky
Aerospace Electronics Co.

This article provides a comprehensive review of the various types of ground plane modifications, with examples illustrating both commonly-used and alternative structures

Different microstrip circuits with modified ground plane are considered in this article. The ground plane aperture (GPA), ground plane lossy aperture (GPLA), and defected ground structure (DGS) provide numerous advantages for microstrip elements and devices. DGS resonators find application in a large number of microstrip circuits where a frequency notch can reduce complexity and enhance performance. GPA is mainly used to increase the impedance in a section of a microstrip, allowing higher impedance lines and higher Q printed inductors. The applications of the GPA and GPLA include termination, attenuator, LPF, directional coupler, phase shifter, and Wilkinson divider.

Defected Ground Structure (DGS)

Planar transmission lines are broadband, low cost and provide compact dimensions and light weight. The most popular microstrip line includes a conductor trace on one side of a substrate and a single ground plane on the other side. Usually, a designer of microstrip circuits focuses on the analysis, synthesis, and calculation of the microstrip circuit (conductor trace), including configuration, dimensions, and structure of the microstrip conductor, while the ground side remains a complete metallization structure. However, the ground plane structure can be modified to improve electrical performance and reduce size of a microstrip circuit. In recent years, there have been several new designs of microstrip circuits with defected ground structure (DGS) [1 - 20], etc. Microstrip lines with DGS have a much higher impedance and an increased slow-wave factor as compared to conventional transmis-

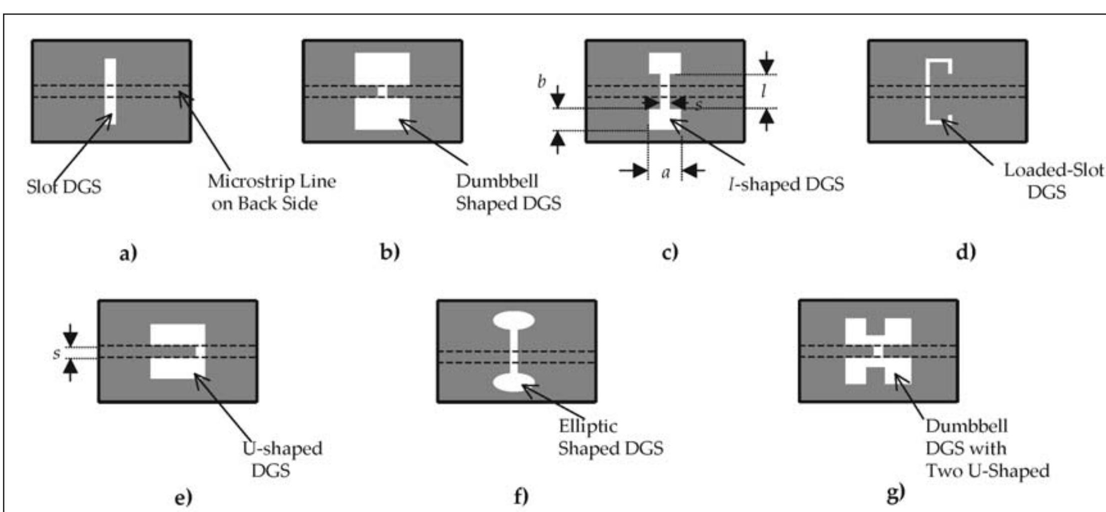

Figure 1 · Some resonant structures used for defected ground structure (DGS) applications.

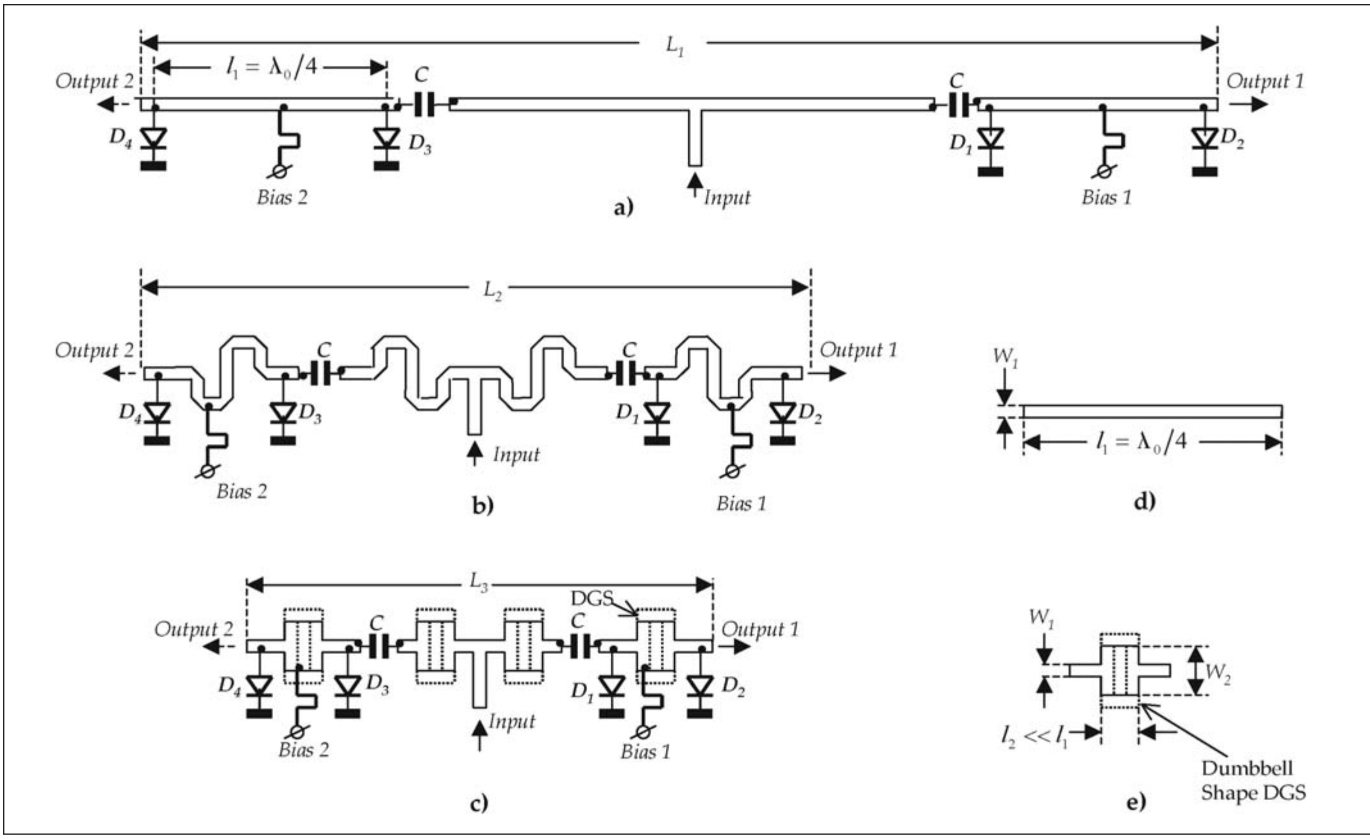

Figure 2 · The use of DGS in microstrip switch circuits.

sion lines. The DGS is attractive as it enables unwanted frequency rejection and circuit size reduction. The DGS is a new type of microstrip design that exhibits well-defined stopbands and passbands in the transmission characteristics, and as such it finds many applications in microwave printed circuits: filters [2, 3, 5, 6, 8, 9, 12, 14, 15, 16], dividers [8], amplifiers [4, 7, 14, 2], oscillators [20], switches [1], directional couplers [8, 13, 15], antennas [17], etc.

The 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 bandstop ("notch") property. The DGS applied to a microstrip line creates a resonance in the circuit, with the resonant frequency controllable by changing the shape and the size of the slot.

The equivalent circuit of the DGS can be represented by a parallel *LC* resonant circuit in series with the microstrip line. 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 microstrip line. This combination of DGS elements and microstrip lines yields sharp resonances at microwave frequencies which can be controlled by changing shape and size of the DGS circuitry. The shape and size of the DGS slot controls both the fundamental resonant frequency and higher order resonances. The size of the p.c. board area is also considered. To fulfill the different requirements, a variety of DGS shapes have evolved over time, including dumbbell, periodic, fractal, circular, spiral, *L*-, and *H*-shaped structures.

Figure 1 shows several resonant structures that may be used. The basic element of DGS is a resonant gap or slot in the ground surface (Fig. 1a), placed directly under the transmission line and aligned for efficient coupling to the line. The dumbbell-shaped DGS (Fig. 1b) includes two wide defected areas connected by a narrow slot. The conventional dumbbell-shaped DGS has been modified into an I-shaped DGS, as shown in Figure 1c. The frequency control of the I-shaped DGS is accomplished by adjusting the length of the transverse slot and the dimensions a and b. The stopband characteristic of the DGS in Fig. 1c depends on l, which is the distance between two rectangular lattices. In the *U*-shaped structure of Figure 1e, the loaded Q-factor increases as distance s decreases.

Elliptic DGS cells are also obtained by etching a slot that connects two elliptic DGS shapes in a

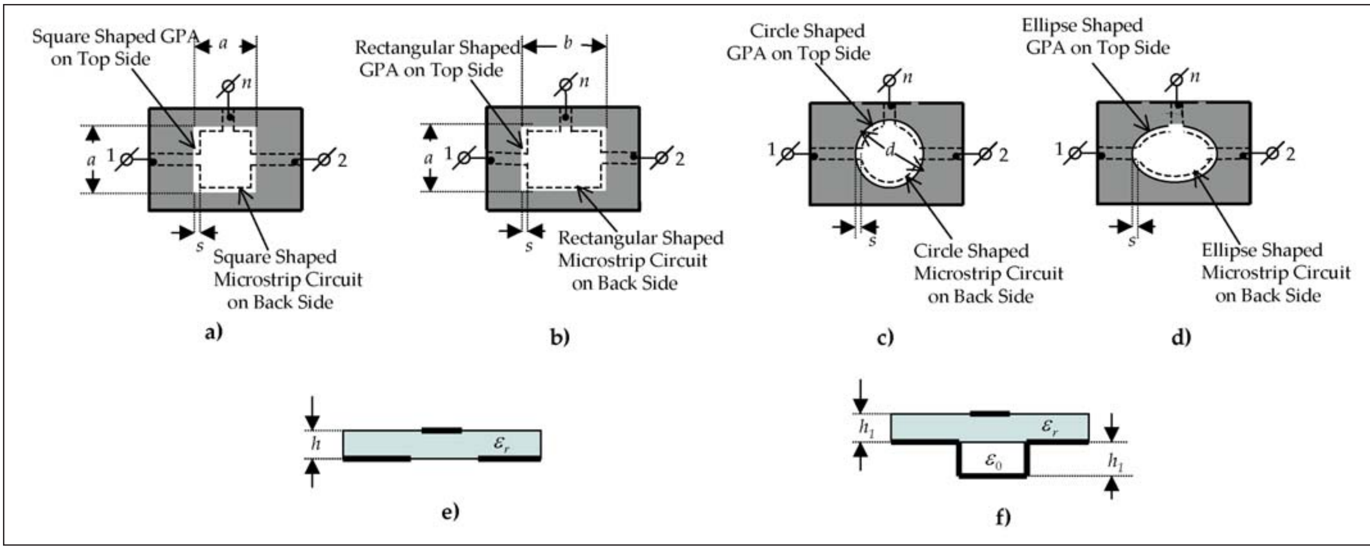

Figure 3 · Microstrip ground plane aperture (GPA) structures.

microstrip ground plane (Fig. 1f) [12]. Figure 1g represents the DGS unit composed of two *U*-shaped slots connected by a transverse slot. This DGS section can provide cutoff frequency and attenuation pole without any periodicity, unlike other DGS [11, 15].

Microstrip Switches

The SPDT switch shows [1] a very similar performance to the conventional shunt-type switch, but the circuit size is reduced through the use of DGS patterns. Lengths of microstrip lines for the diode connection are reduced by about 50%. The conventional narrowband shunt diode switch topology with straight quarter-wave diode spacing (Fig. 2a) is too large in the *L*-band. Figure 2b illustrates the same switch with the meander connected line to reduce physical dimensions. The SPDT switch [1] shows very similar performance to the conventional shunt-type switch, but the circuit size is reduced through the use of DGS patterns. Figure 2c shows a microminiature SPDT switch based on the dumbbell-shaped DGS. The slow-wave effect is utilized to reduce the circuit size of the RF circuitry. Insertion loss of the conventional quarter wavelength microstrip line is identical to that of the DGS microstrip line. The DGS microstrip switch network (Fig. 2c) provides a 50% size reduction as compared to the straight line switch (Fig. 2a), and a 30% size reduction as compared to the meander line network (Fig. 2b).

The main disadvantage of the defected ground technique is that it radiates. Also, the special configuration of the DGS requires special technology process for implementation of the two-layer structure.

Ground Plane Aperture (GPA)

In this paper, we propose microstrip circuits with ground plane aperture (GPA) and ground plane lossy aperture (GPLA). The GPA can be square (Fig. 3a), rectangular (Fig. 3b), circular (Fig. 3c), or elliptic (Fig. 3d) depending on the structure of the microstrip circuit. Figure 3e and Figure 3d show the side view of the GPA and the GPA with cavity in the GPA area. Compared to the DGS, the GPA has a simple structure and a potentially great applicability to the design of microwave circuits. The GPA can provide reduction of 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 GPA has interesting applications for inductors, transitions between different transmission lines, filters, dividers/combiners, phase shifters, directional couplers, baluns, etc.

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

1. Physical dimensions (length a, width b, or diameter d for circular shape) of GPA should be less than $\lambda/4$ (λ is the guide wavelength) to avoid radiation from microstrip circuitry;
2. $3W_c$ rule: the space s between a microstrip outer conductor (in 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;
3. Thickness of the GPLA should be less than the skin layer depth.

Microstrip circuits in Figure 3 are represented as n-port networks. In this paper, the following circuits with GPA and GPLA will be considered: termination (n = 1); transition between different lines, attenuator, LPF (n = 2); Wilkinson divider (n = 3); differential phase shifter; directional coupler (n = 4).

Microstrip-to-Coaxial Transition

The simplest application of the microstrip aperture in the microstrip-to-coaxial transition is shown in Figure 4. Such a transition is fabricated by drilling a hole in the microstrip substrate. The center pin is inserted through the hole and connected to the microstrip circuit. The shield of the coax connector is connected to the ground plane of the microstrip line. The microstrip ground plane is interrupted by a GPA (circular aperture) etched around the center pin. The main parasitic factor of perpendicular transitions like this one is the inductance caused by ground currents which must flow around the circumference of the outer coax conductor to reach the underside of the microstrip section. This problem is alleviated by reducing the diameter of the circular aperture in the GPA, effectively providing a shortcut for ground currents from the outer edges of the coax shield. If the aperture is made too small, however, shunt capacitance from the center pin to the substrate ground once again degrades the performance of the junction. It was discovered [19] that offsetting the aperture (a ≠ b) as shown in Figure 4a can greatly improve the performance of the transition.

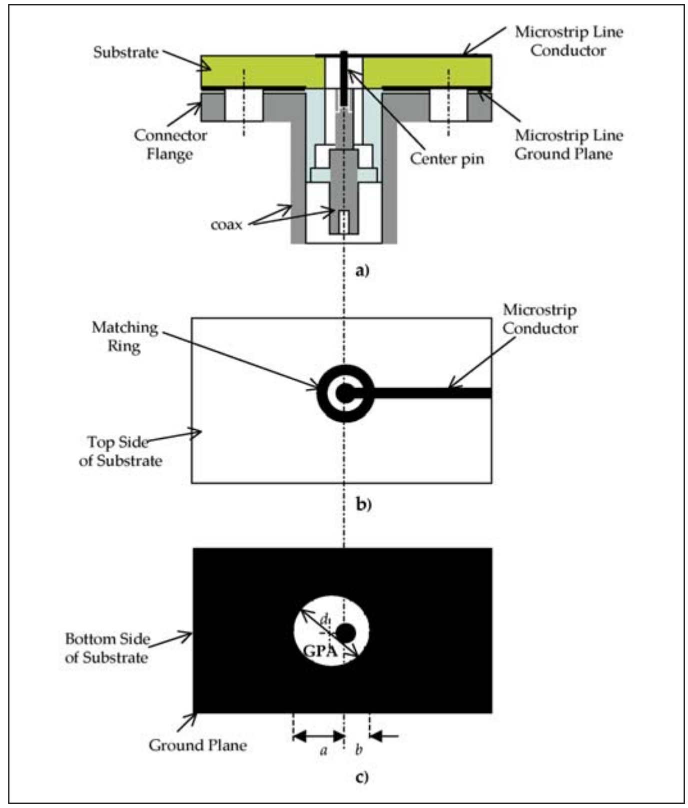

Figure 4 · Application of the GPA for microstrip-to-coaxial connector transition.

Stepped-Impedance Lowpass Filter

The layout of a stepped-impedance LPF realized on a combination of traditional microstrip line and microstrip line with the GPA is shown in Figure 5. This design uses series high impedance inductive elements based on the microstrip line with the GPA and low impedance shunt microstrip capacitive elements. The side view (Fig. 5b) shows the cavities under the GPA which help avoid possible radiation from the inductive elements. This combination allows a very large impedance ratio and, therefore, very good stopband performance, in additional to small size. The inductor element is realized by meander line with the GPA in order to minimize size. This filter was implemented on a 10-mil TLE-95 substrate (from Taconic)

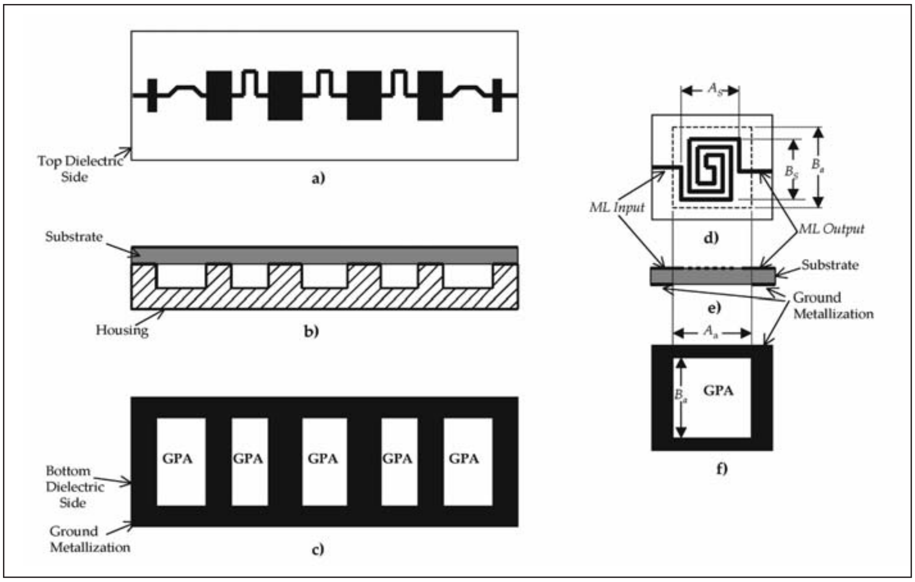

Figure 5 · A stepped-impedance LPF using a combination of conventional microstripline and GPA.

and provided an insertion loss of less than 0.3 dB, a VSWR of less than 1.2 in the frequency range up to 1.1 GHz, and attenuation of more than 70 dB in the frequency range between 2.0 and 5.0 GHz. At lower frequencies, lumped element LPFs are more practical. LPF can be realized based on lumped element print planar inductors with the GPA. The conventional spiral inductors have some disadvantages. The spiral inductor requires two metal layers, one for spiral inductor itself and another for an air bridge to provide crossover connection between inductor center and outer circuitry. The signal-layer spiral inductors [21] consist (see Fig. 5d) of two spirals: the first one spiraling from the input to the center in the clockwise direction, and the second one spiraling from the center terminal to the output terminal in a counterclockwise direction. To minimize parasitic capacitance between the spiral conductor and the ground plane, the GPA with dimensions A_a, B_a is used under the spiral inductor (Fig. 5f). The GPA provides a reduction in width of the spiral microstrip line due to a significant diminishing of the passband ripple (for LPF applications) in the dual planar structure. The maximum outside spiral dimen-

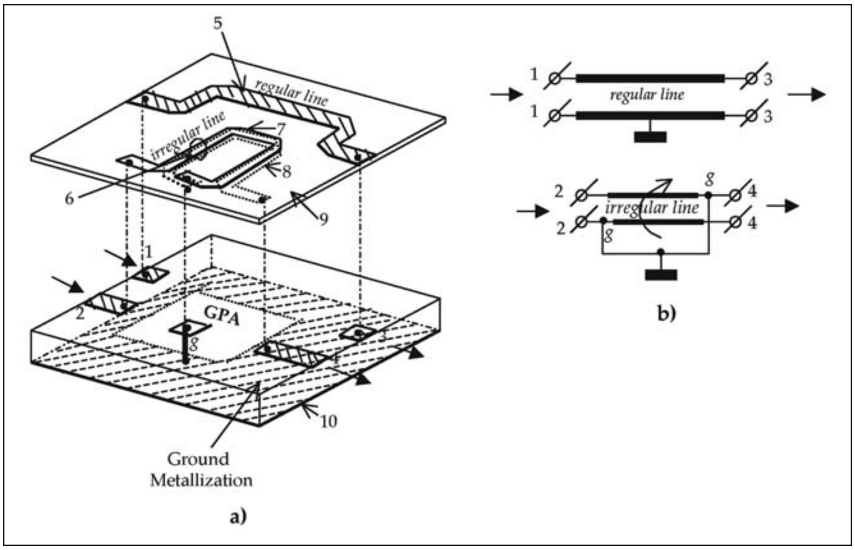

Figure 6 · A differential 180° phase shifter implemented with GPA.

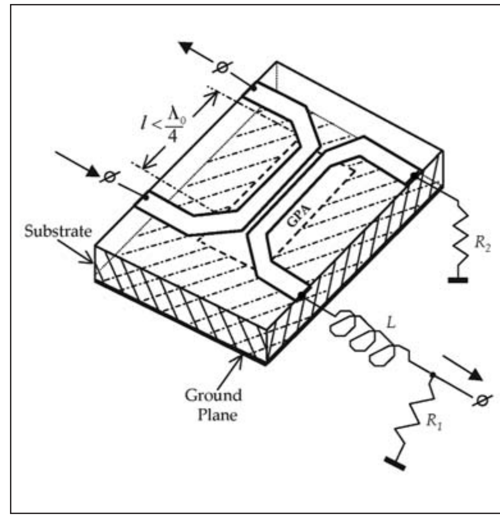

Figure 7 · Coupled-line directional coupler implemented using GPA.

sions A_S, B_S should be less than λ/300 (λ is the spiral guide wavelength). The miniature LPF with three single-layer inductors and GPA was designed for VHF range with a band-pass loss less than 0.6 dB, input and output return loss greater than 20 dB, and second harmonic attenuation greater than 30 dB [21].

Phase Shifters

RF and microwave phase shifters have many applications in various equipment such as phase discriminators, beam forming networks, power dividers and phase array antennas. Modern phase shifters are mainly based on PIN diodes, field emitting transistors (FET) and ferromagnetic materials. In recent years, microelectromechanical-based (MEMS) solutions have been developed and presented [22]. These phase shifters are based on the GPA structure with air cavity (Fig. 3f). The phase velocity of an electromagnetic wave in the GPA with cavity is a function of the thickness of the stacked air gap (h_2) and substrate (h_1) as is seen in Figure 3f. The phase shift occurs because the permittivity of the region between the microstrip line and the ground plane changes as the air gap is introduced. The effective permittivity ε_{eff} can be derived approximately from adding the dielectric capacitances in series:

$$\varepsilon_{eff} = \frac{\varepsilon_r \varepsilon_0 (h_1 + h_2)}{\varepsilon_r h_2 + \varepsilon_0 h_1}$$

where ε_r and h_1 are permittivity and thickness of the dielectric substrate, and ε_0 and h_2 are permittivity and thickness of the air gap, respectively.

Irregular lines with the GPA can be used for 180° phase shifter, transformer, balun, and BPF. Figure 6a illustrates the differential 180° phase shifter that uses a regular (5) and an irregular (6) line with the GPA. The irregular line includes [21, 23] two coupled conductors (7) and (8) with strong magnetic coupling and the GPA in the coupling area. Since the irregular line is almost entirely unaffected by the RF ground plane, capacitances between the line and the ground plane are negligible compared to the capacitances between conductors. The strong magnetic coupling allows for small length of the irregular line. This effect is intensified by the elimination of the GPA from the area directly below the coupled lines. Strong magnetic coupling between lines supports miniature dimensions and an increased bandwidth. The equivalent circuit of a 180° phase shifter is shown in Figure 6b. The output port (4) of the first coupled conductor is electrically connected to the diagonal end of the second coupled conductor (2) and dc-coupled to ground located on the base dielectric substrate (10). The segment providing the diagonal connection should be as short as possible. This can be achieved by bending the line. The RF ground has to be apart from the irregular line and close to the appropriate input/output lines, that is, there should be no RF ground plane in the area of coupled conductors. The irregular line contains two parallel broadside coupled conductors—(7) top, and (8) bottom) located on the two sides of the thin dielectric substrate (9). Experimental characteristics of this phase shifter are given in [21, 24].

In general, the characteristic impedance of a microstrip line is 20 to 120 ohms. The upper limit is set by production tolerance due to the extremely small ratio W/h and the appearance of the higher-order modes. However, some microstrip devices require greater characteristic impedance, for example, branch-line directional couplers for wide frequency range or for unequal power division greater than 10 dB. To overcome the high impedance limitation, a much wider microstrip conductor is required. Due to the additional effective inductance of the high impedance microstrip line with GPA, it provides higher effective permittivity and characteristic impedance than those of a conventional microstrip line. The branch-line coupler consists of a main line that is coupled to a secondary line by $\lambda_0/4$-long branches spaced by $\lambda_0/4$. The bandwidth of the branch coupler can be enlarged by increasing the number of branches. However, branch-line couplers with more than four branches are difficult in microstrip because the end branches require impedances that reach the upper limits of practical realization. The GPA under end branches can enable implementation of broadband branch couplers with more than four branches.

The power split for the two-branch divider is specified at [21]

$$m = \frac{P_3}{P_4} = \frac{1}{Y_1^2} = \frac{1}{Y_2^2 - 1}$$

where P_3 and P_4 are power at output 3 and output 4 respectively (port 1 is input, port 2 is isolated port); Y_1 and Y_2 are normalized admittances of the branches and connected lines respectively. Then the normalized admittances are equal so that

$$Y_1^2 = \frac{1}{m}, \quad Y_2^2 = \frac{m+1}{m}$$

For $m > 3$, it is difficult to realize the corresponding ratio of admittances; therefore, the maximum practical split used is $m = 3$ (4.8 dB). For 10 dB coupling the microstrip line should have a characteristic impedance greater than 150 ohms. To realize a high impedance line, the GPA can be used in the two-branch coupler. To avoid radiation from the GPA, cavities in the housing under the GPA should be implemented. The depth of the cavity (space between the dielectric and the bottom of the metal cavity) depends on the characteristic impedance of the high impedance microstrip lines in these areas.

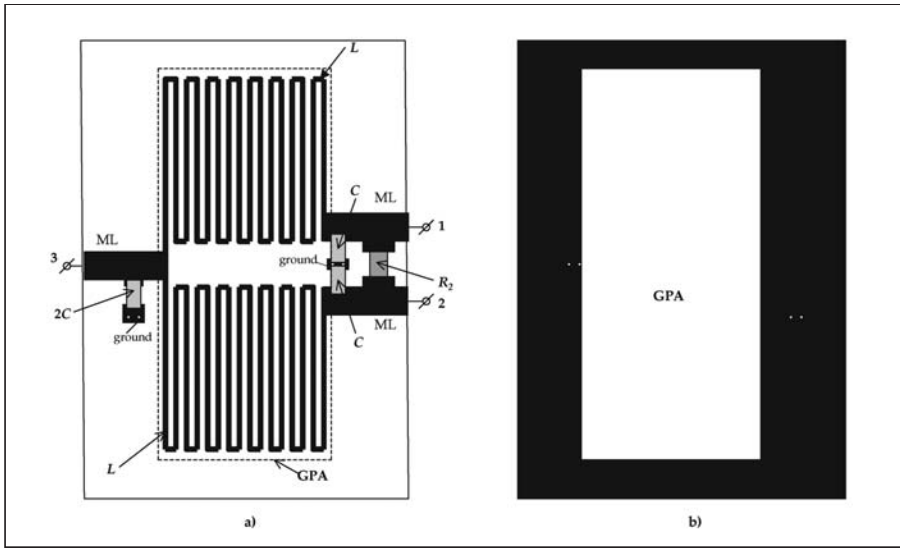

Figure 8 · Wilkinson divider using lumped element components, with GPA placed below the inductor.

Directional Coupler

In the VHF and UHF range, the classic directional coupler with a coupled-line length of $\lambda_0/4$ has large dimensions, which makes it difficult to build. Figure 7 illustrates the modified coupled-line directional coupler with the GPA and two coupled lines which have a very short geometric length (less than $\lambda_0/4$). Design of microstrip coupled-line directional couplers is tied to specific difficulties. In such couplers, odd mode oscillations propagate in air and the dielectric substrate, while even-mode oscillations propagate in the dielectric substrate only. As a result, codirectional propagation (forward direction) appears in the secondary line. Thus, the conventional microstrip coupled-line directional coupler has a low directivity. To provide high directivity, the GPA is used. The GPA reduces the effective dielectric constant for the even mode considerably more than it does for the odd mode. The GPA dimensions and dielectric substrate thickness should be optimized. The main problem of the short ($l < \lambda_0/4$) coupled line directional couplers is that its degree of coupling varies with frequency. A special compensation circuit LR_1 (Fig. 7) [24] is used to diminish this effect. Experiments have shown that for 30% bandwidth, the present microstrip directional coupler with length $l = 0.05\lambda_0$ (five times less than a traditional directional coupler), $f_0 = 120$ MHz has a coupling flatness of ±0.05 dB, a directivity of more than 23 dB, an insertion loss of less than 0.15 dB, and VSWR of less than 1.15.

Wilkinson Divider

The Wilkinson power divider is relatively large for low-frequency application. To reduce size, the quarter wavelength segments of the Wilkinson divider can be substituted by a π-section lumped element circuit with a series inductor L and two parallel capacitors C [21]:

$$L = \frac{z}{2\pi f_0}, \quad C = \frac{1}{2\pi f_0 z}$$

where z is characteristic impedance of the quarter wavelength segments.

Figure 8 shows the layout of the lumped element Wilkinson divider.

Capacitors of two segments at the input of the power divider may be replaced by a single capacitor of twice the value (2C, Fig. 8,a). The GPA (Fig. 8,b) below the meander inductors offers certain advantages: low parasitic capacitance between the meander inductors and ground plane, higher impedance of the meander inductor line which reduces size. This divider occupies an area ten times smaller than the conventional distributed Wilkinson divider [21].

Patch Antennas

Coupling is a common and significant problem in co-site antenna design. Multiple antennas are often cosited on a single platform and if their close proximity results in coupling, degradation of both reception and transmission of signals will occur [17]. This may result in unexpected resonant frequencies and radiation patterns, both of which are undesirable to the designer. The effect of a simple GPA structure in improving the mutual coupling between the elements of a two element circular patch array is studied using the simulation data.

Resistive Devices

The special Ground Plane Lossy Aperture (GPLA) can be used for implementation of planar resistors and attenuators with high surface resistance R_S In most conventional microstrip designs (Fig. 9c) metal conductor thickness t_c and ground plane thickness t_G should be greater than approximately three times the skin depth δ to minimize microstrip line loss. Skin depth of a conductor or a ground plane is defined as the distance to the metal where the current density drops to 1/e of the maximum current density, or 37% of its value at the surface of the conductor. To increase the surface resistance for a termination or an attenuator, the thickness of the ground plane in the termination or the attenuator area is chosen to be significantly less than the skin layer thickness $t_{GPLA} < \delta$ (Fig. 9d). The GPLA is the GPA with deposited film of lossy metal in the aperture area. This film has low thickness 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 [21]. For high attenuation values with limited dimensions, the conductor of attenuator or resistor can be given a meander or a spiral line shape. Figure 9a and Figure 9b show the sketch of the planar attenuator and the termination respectively with the GPLA in the area of the microstrip circuit.

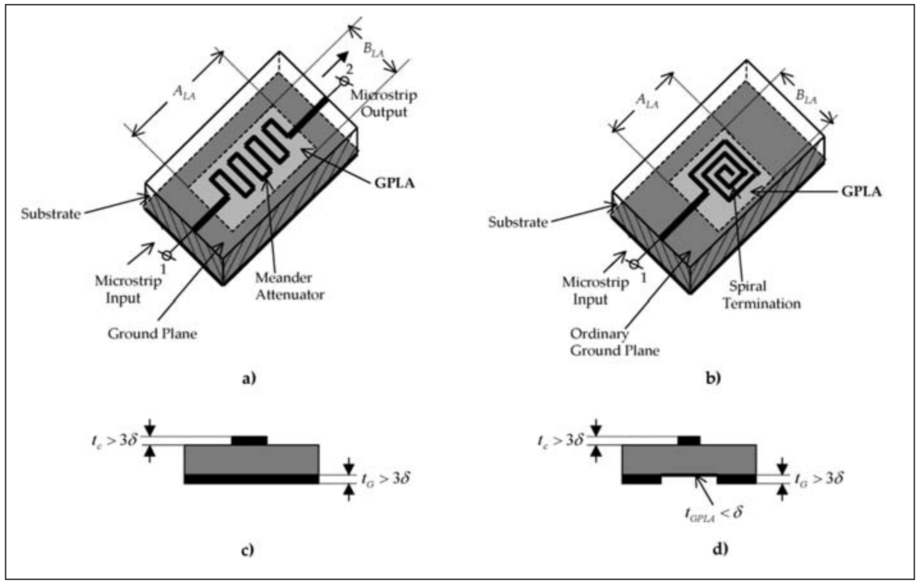

Figure 9 · Planar attenuator and terminations using GPLA.

Author Information

Leo G. Maloratsky received his MSEE from the Moscow Aviation Institute and his PhD from the Moscow Institute of Communications in 1962 and 1967, respectively. Since 1962, he has been involved in the research, development and production of RF and microwave integrated circuits at the Electrotechnical Institute, and he was assistant professor at the Moscow Institute of Radioelectronics. He has worked as a staff engineer at Allied Signal and a principal engineer at Rockwell Collins. In 2008 he joined Aerospace Electronics Co. He is author of four monographs, one textbook, over 50 articles, and 20 patents. His latest book is *Passive RF and Microwave Integrated Circuits,* 2004, Elsevier.

References

1. Dong-Wook Kim, "Small-Sized High Power PIN Diode Switch with Defected Ground Structure for Wireless Broadband Internet," *ETRI Journal,* Vol.1, February 2006, pp. 84-86.

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

3. M. K. Mandal, *An Improved Low Pass Filter Using Microstrip Defected Ground Structure,* Dept. of Electronics & Electrical Communication Engineer-

ing, Indian Institute of Technology, 2005.

4. Si-Gyun Jeong, et al., "Harmonic Reduction Amplifier Using High Impedance Bias Line with Defected Ground Structure (DGS)," *IEEE European Microwave Conference,* 2002, 32nd vol., Issue, 4-6 Oct. 2002: 1-4.

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

6. 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.

7. Y-C Jeong, et al., "Amplifier Design Using a High Impedance Bias Line a Defected Ground Structure (DGS)," *Microwave Journal,* April 2004.

8. J. Yun, et al., "Design Application of Defected Ground Structures," Ansoft Corporation, 2003.

9. Y. B. Cho, et al., "Small-sized Quasi-elliptic Function Microstrip Low Pass Filter on Defected Ground Structure and Open Stubs," *Microwave Journal*, February 2004.

10. G. Breed, "An Introduction to Defected Ground Structures in Microstrip Circuits," *High Frequency Electronics,* November 2008.

11. D. Ahn, et al., "A Design of the Low-Pass Filter Using the Novel Microstrip Defected Ground Structure," *IEEE Trans. Microwave Theory Tech.,* 2001, vol. 49, No. 1, pp. 86 - 93.

12. X. Q. Chen, et al., "Build Lowpass Filters With Elliptic DGS," *Microwaves & RF,* January 2009.

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

14. X. Q. Chen, et al., "A Novel Dual Band Transmitter Using Microstrip Defected Ground Structure," PIER 83, 1-11, 2008.

15. S. K. Parui., et al., "A New Defected Ground Structure for Different Microstrip Circuit Applications," *Radioengineering,* Vol. 16, No. 1, April 2007.

16. S. Y. Huang, et al., "Compact U-Shaped Dual Planar EBG Microstrip Low-Pass Filter," *IEEE Transactions on Microwave Theory and Techniques,* Vol. 53, No. 12, December 2005.

17. C-Y. Chiu, "Reduction of Mutual Coupling Between Closely-Packed Antenna Elements," *IEEE Transactions on Antennas and Propagation,* 2007, 55 (6), pp.1732-1738.

18. H. Liu, et al., "Novel Two-Dimensional (2-D) Defected Ground Array for Planar Circuits," *Active and Passive Electronic Components,* September 2004, Vol. 27, pp. 161-167.

19. M. A. Morgan, *Millimeter-Wave MMIC and Applications, California Institute of Technology Pasadena, California* (Defended March 24, 2003).

20. J.-S. Park, "An Equivalent Circuit and Modeling Method for Defected Ground Structure and its Application to the Design of Microwave Circuits," *Microwave Journal,* November 2003.

21. L. G. Maloratsky, , *Passive RF and Microwave Integrated Circuits,* Elsevier, 2004.

22. J. Yip, "MEMS Micro-Ribbons for Integrated Ground Plane Microstrip Delay Line Phase Shifter," Thesis Submitted to the Faculty of Graduate Studies of the University of Manitoba in Partial Fulfillment of the Requirements for the Degree of Master of Science, Department of Electrical and Computer Engineering University of Manitoba Winnipeg, Manitoba, Canada 2008.

23. L. G. Maloratsky, "Design Regular- and Irregular-Print Coupled Lines," *Microwave & RF,* September 2000, pp. 97-106.

24. L. G. Maloratsky, et al., "Miniature Directional Coupler," U.S. Patent, No. 5,424,694, June 13, 1995.