Coplanar Waveguide: A Surface Strip Transmission Line Suitable for Nonreciprocal Gyromagnetic Device Applications

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Abstract—**A coplanar waveguide consists of a strip of thin metallic film on the surface of a dielectric slab with two ground electrodes running adjacent and parallel to the strip. This novel transmission line readily lends itself to nonreciprocal magnetic device applications because of the built-in circularly polarized magnetic vector at the air–dielectric boundary between the conductors. Practical applications of the coplanar waveguide have been experimentally demonstrated by measurements on resonant isolators and differential phase shifters fabricated on low-loss dielectric substrates with high dielectric constants. Calculations have been made for the characteristic impedance, phase velocity, and upper bound of attenuation of a transmission line whose electrodes are all on one side of a dielectric substrate. These calculations are in good agreement with preliminary experimental results. The coplanar configuration of the transmission system not only permits easy shunt connection of external elements in hybrid integrated circuits, but also adapts well to the fabrication of monolithic integrated systems. Low-loss dielectric substrates with high dielectric constants may be employed to reduce the longitudinal dimension of the integrated circuits because the characteristic impedance of the coplanar waveguide is relatively independent of the substrate thickness; this may be of vital importance for low-frequency integrated microwave systems.**

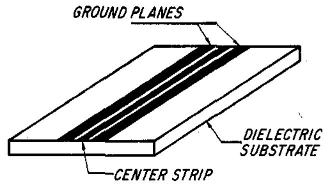

Fig. 1. Coplanar waveguide (CPW), a surface strip transmission line.

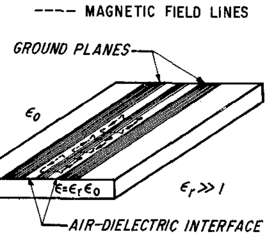

Fig. 2. RF magnetic field configuration in a CPW.

MICROWAVE integrated circuits offer system engineers prospects of small, batch processed modules for radar and communication systems. In the past, radar and communication systems included a variety of nonreciprocal magnetic devices. These devices require circularly polarized RF magnetic fields for their operation, and present microstrip and strip lines do not provide such fields. In addition, the ground plane of these lines, which is located on the opposite side of a dielectric substrate, is not easily accessible for shunt connections necessary for many active microwave devices. Direct dependence of the characteristic impedance on the thickness of the substrate makes it difficult to use a low-loss, high-dielectric-constant material, such as a temperature-compensated ceramic. This is a definite drawback for low-frequency operation where size consideration dominates. All these disadvantages may either be overcome or alleviated by a novel integrated-circuit transmission-line configuration in which all conducting elements, including the ground planes, are on the same side of a dielectric substrate. This is called the coplanar waveguide, a surface-strip transmission line.

A coplanar waveguide (CPW) consists of a strip of thin metallic film deposited on the surface of a dielectric slab with two ground electrodes running adjacent and parallel to the strip on the same surface, as shown in Fig. 1. There is no low-frequency cutoff because of the quasi-TEM mode of propagation. However, the RF electric field between the center conducting strip and the ground electrodes tangential to the air–dielectric boundary produces a discontinuity in displacement current density at the interface, giving rise to an axial, as well as transverse, component of RF magnetic field. These components provide the elliptical polarization needed for nonreciprocal gyromagnetic microwave device applications [1]. If the relative dielectric constant ϵ_r of the substrate is very large compared to unity, the magnetic field at the interface is nearly circularly polarized with the plane of polarization perpendicular to the surface of the substrate, as shown in Fig. 2. Such a transmission line readily lends itself to integrated-circuit fabrication techniques and nonreciprocal gyromagnetic device applications because of the built-in circularly polarized magnetic vector which is easily accessible at the surface of the substrate. The coplanar configuration of all conducting elements permits easy connection of external shunt elements such as active devices as well as the fabrication of series and shunt capacitances. It is also ideal for connecting various elements in monolithic microwave integrated circuits built on semiconducting substrates or ferromagnetic semiconductors. All ground planes may be connected together through a metallic capsule as shown in

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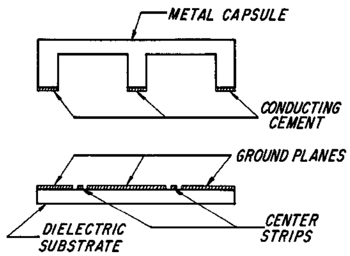

Fig. 3. Metallic capsule for CPW ground connections.

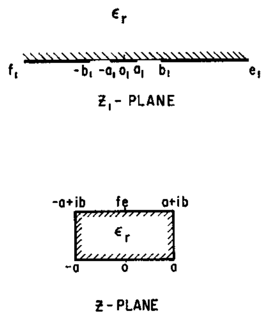

Fig. 4. Conformal mapping transformation of the upper half-plane of a CPW into the interior of a rectangle.

Fig. 3, serving both as a common ground and a protective cover. Because of the high dielectric constant of the substrate, most of the RF energy is stored in the dielectric and the loading effect of the grounded cover is negligible if it is more than two slot widths away from the surface.

Characteristic impedances Z_0 of CPWs fabricated on dielectric half-planes with relative dielectric constants ϵ_r have been calculated as a function of the ratio a_1/b_1, where $2a_1$ is the width of the center strip and $2b_1$ is the distance between two ground electrodes. A zeroth-order quasi-static approximation is employed. The dielectric half-plane Z_1 in Fig. 4 may be transformed to the interior of a rectangle in the Z-plane by conformal mapping [2]:

$$\frac{dZ}{dZ_1} = \frac{A}{(Z_1^2 - a_1^2)^{1/2}(Z_1^2 - b_1^2)^{1/2}} \tag{1}$$

where A is a constant. The ratio a/b of the rectangle in the Z plane may be evaluated by multiplying both sides of (1) by dZ_1 and carrying out the integration

$$a + jb = \int_0^{b_1} \frac{A\,dZ_1}{(Z_1^2 - a_1^2)^{1/2}(Z_1^2 - b_1^2)^{1/2}} \cdot \tag{2}$$

As a result

$$\frac{a}{b} = \frac{K(k)}{K'(k)} \tag{3}$$

where

$k = a_1/b_1$,

$K(k)$ = complete elliptical integral of the first kind [3],

$K'(k) = K(k')$,

$k' = (1-k^2)^{1/2}$.

If the relative dielectric constant of the material filling the rectangle in the Z plane of Fig. 4 is ϵ_r, a uniform electric field E is set up in the capacitor with the top and bottom plates charged up to opposite polarities and the capacitance per unit length of the line, including the empty space half-plane, is

$$C = (\epsilon_r + 1)\epsilon_0 \frac{2a}{b} \cdot \tag{4}$$

A zeroth-order quasi-static approximation has been employed to estimate the phase velocities and the characteristic impedances of CPWs. The approximation simply treats the CPW as a transmission line totally immersed in a dielectric with effective dielectric constant $(\epsilon_r+1)/2$. The resulting phase velocity is

$$v_{ph} = \left(\frac{2}{\epsilon_r + 1}\right)^{1/2} c \tag{5}$$

where c is the velocity of light in free space and the characteristic impedance is

$$Z_0 = \frac{1}{C v_{ph}} \cdot \tag{6}$$

The ratio v_{ph}/c is shown in Fig. 5 as a function of ϵ_r. In Fig. 6 the characteristic impedance Z_0 is shown as a function of a_1/b_1 with the relative dielectric constant ϵ_r as a parameter ranging from unity to 250. Experimental confirmation has been obtained at three points shown on the same figure with transmission lines fabricated on substrates of relative dielectric constant $\epsilon_r = 9.5$, 16, and 130, respectively. The calculated characteristic impedance of a parallel-strip coplanar line, the dual of the CPW, is shown in Fig. 7 as a function of a_1/b_1 with the relative dielectric constant ϵ_r of the substrate as a parameter [4]. The configuration of this line can be found on the same figure.

The thickness of the dielectric substrate becomes less critical with higher relative dielectric constants. In the CPW configuration the characteristic impedance increases by less than 10 percent when the thickness of the substrate is reduced from infinity to $b_1 - a_1$, the width of the slots, for infinitely large ϵ_r. In practice, the thickness t of the substrate should be one or two times the width of the slots. It is obvious that the finite thickness of the substrate will influence the dispersion characteristics of the transmission line but no estimate has been made on the extent of the effect. The experimentally measured dispersion characteristic of a coplanar waveguide fabricated on a single-crystal rutile substrate is shown on the frequency versus βL plot of Fig. 8. It is not known what portion of the dispersion is caused by the crystal anisotropy of the substrate and what portion is attributed to the inherent characteristics of the CPW mode of propagation on a dielectric half-space.

At microwave frequencies up to X band the attenuation of a CPW is due mainly to the copper loss of the conductors if the loss tangent of the dielectric is 0.001 or smaller. Measurements made on a 16.6-ohm CPW fabricated on a rutile substrate ($\epsilon_r \cong 130$, $k = \frac{1}{3}$, center conductor width is 0.025

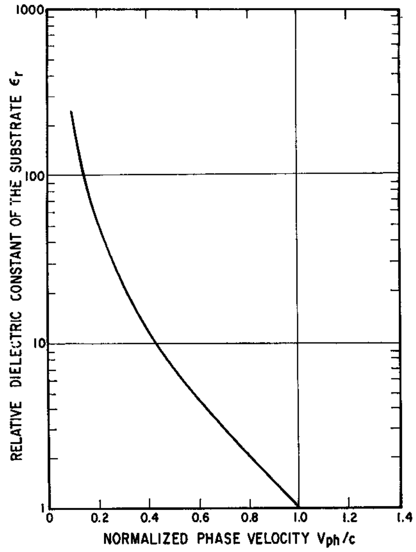

Fig. 5. Relationship between the relative dielectric constant ϵ_r of the substrate and the normalized phase velocity v_{ph}/c in a CPW.

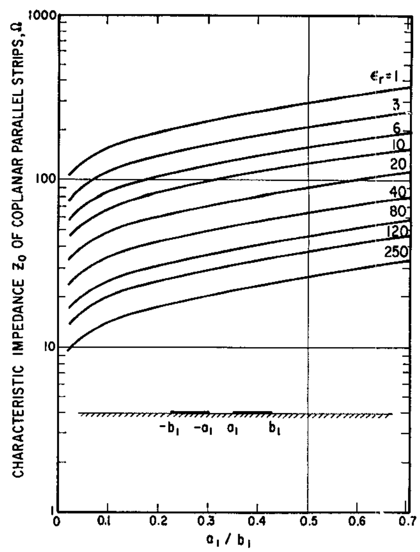

Fig. 7. Characteristic impedance Z_0 of coplanar parallel strips as a function of the ratio a_1/b_1 with the relative dielectric constant ϵ_r as a parameter.

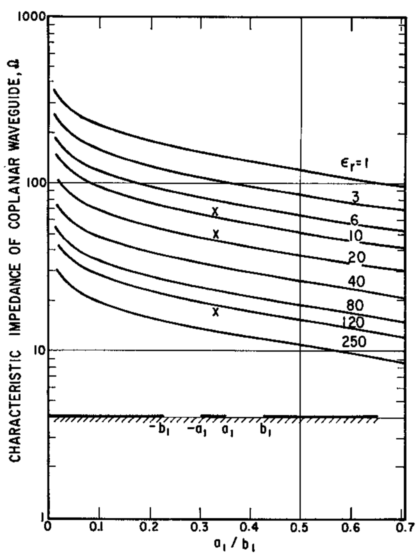

Fig. 6. Characteristic impedance Z_0 of CPW as a function of the ratio a_1/b_1 with the relative dielectric constant ϵ_r as a parameter

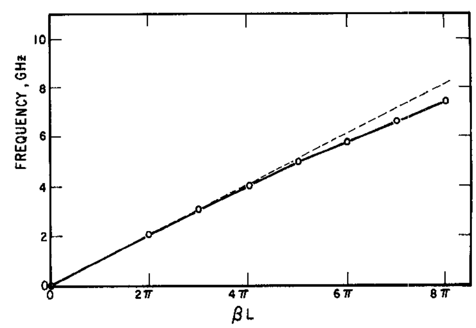

Fig. 8. Dispersion characteristics of a CPW on a TiO_2 substrate.

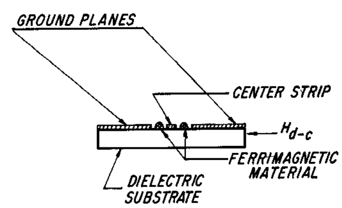

Fig. 9. Resonant isolator or differential phase shifter in CPW configurations.

inch, thickness of gold film is 2 microns, thickness of the dielectric substrate is 0.025 inch), yielded a Q of 173 at 4 GHz, corresponding to an attenuation of only 0.158 dB per wavelength.

Other design considerations include radiation problems when the total distance from one ground plane to another approaches $\lambda/2$. This will pose a limit on the dielectric constant of the substrate employed at a given frequency and the transverse dimension of the transmission line. CPWs can be easily adapted to coaxial systems using OSM connectors. Broad-band (2–12 GHz) matching has been achieved with a 50-ohm CPW deposited on a magnesium oxide substrate with $\epsilon_r = 16$.

Nonreciprocal gyromagnetic devices such as resonant isolators and differential phase shifters have been fabricated by attaching ferrimagnetic slabs at the air–dielectric interface between the conductors, as shown in Fig. 9. A differential phase shifter fabricated on an all-magnetic garnet substrate has also been built. A transverse dc magnetic field parallel to the surface of the substrate is required to provide appropriate bias conditions. As shown in Fig. 10, a CPW ferrimagnetic-resonance isolator built on the surface perpendicular to the c axis of a single rutile crystal provides 37-dB isolation at the center frequency of 6 GHz while the forward attenuation is below 2 dB. Overall length of the line is 0.8 inch including a quarter-wave transformer at each end. The center conductor width is 0.030 inch, $k = 0.33$, and the substrate is 0.025 inch thick. Strips of Trans-Tech G-1000 YIG

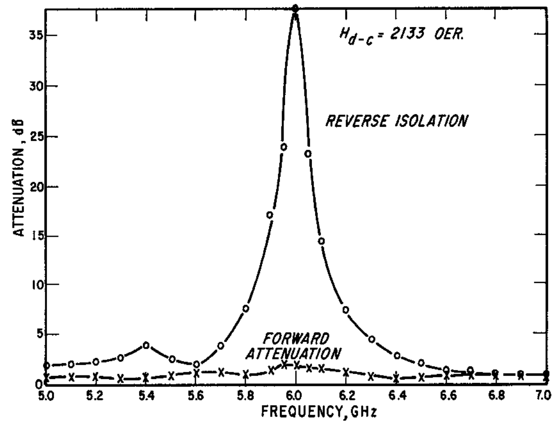

Fig. 10. Performance of a CPW ferrimagnetic-resonant isolator on a single-crystal rutile substrate.

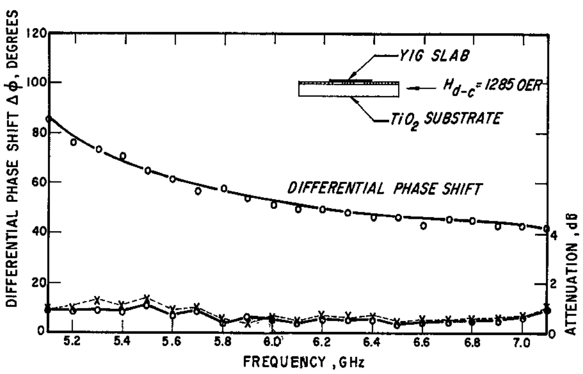

Fig. 11. Performance of a CPW ferrimagnetic differential phase shifter on a single-crystal rutile substrate.

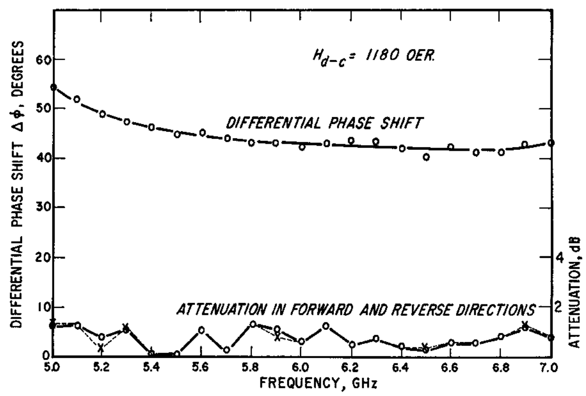

Fig. 12. Performance of a CPW ferrimagnetic differential phase shifter on a YIG substrate.

(0.010 inch×0.005 inch×0.60 inch) are attached by low-loss cement to the rutile surface with the center line of the YIG 0.010 inch from the ground planes. The performance of a phase shifter whose configurations are similar to the previously discussed isolator, are shown in Fig. 11. No attempt has been made to equalize the amount of differential phase shift across the band of frequencies. Average differential phase shift is over 45° while the insertion loss in either direction is less than 1 dB between 5.6 GHz and 7.1 GHz. Higher loss is observed at the lower frequencies which are neaı the ferrimagnetic resonance. Differential phase shift and loss data for a CPW fabricated on a YIG substrate is shown in Fig. 12. A tapered ceramic piece (0.800 inch long, 10° tapering on both ends, $\epsilon_r = 83$) is placed on top to provide the circularly polarized magnetic vector in the ferrite. The amount of differential phase shift varies little with frequency beyond 5.5 GHz. Insertion loss of 1.3 dB or less has been measured from 5.0 GHz to 7.0 GHz without special effort to match the device to the 50-ohm test system. These preliminary results demonstrate the gyromagnetic nonreciprocal device capabilities of coplanar waveguides.

In summary, the practicality of a novel microwave integrated circuit transmission line suitable for nonreciprocal gyromagnetic device applications has been demonstrated. Some preliminary calculations for characteristic impedance, phase velocity, and attenuation characteristics are presented and compared with experimental results. The coplanar configuration of the transmission system not only permits easy shunt connections of external elements, it also adapts well to the fabrication of monolithic integrated circuits.

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