

[72] Inventor **Reinhard H. Knerr**  
**Allentown, Pa.**  
 [21] Appl. No. **864,371**  
 [22] Filed **Oct. 7, 1969**  
 [45] Patented **Apr. 6, 1971**  
 [73] Assignee **Bell Telephone Laboratories Incorporated**  
**Murray Hill, N.J.**  
**Continuation of application Ser. No.**  
**795907, Feb. 3, 1969.**

[56] **References Cited**  
**UNITED STATES PATENTS**  
 3,335,374 8/1967 Konishi ..... 333/1.1  
 3,510,804 5/1970 Hashimoto et al..... 333/1.1

*Primary Examiner*—Herman Karl Saalbach  
*Assistant Examiner*—Tim Vezeau  
*Attorneys*—R. J. Guenther and E. W. Adams, Jr.

[54] **THIN FILM Y-JUNCTION CIRCULATOR**  
**7 Claims, 5 Drawing Figs.**

[52] U.S. Cl..... 333/1.1,  
 333/84  
 [51] Int. Cl..... **H01p 1/32**  
 [50] Field of Search..... 333/1.1, 84  
 (M)

**ABSTRACT:** A Y-junction strip line circulator adapted to thin film construction techniques. It has been discovered that if the 12 crossings in a Y-junction circulator of the type having two split inner conductors per branch are laid down in a perfectly symmetrical manner, the capacitance of these crossings can be made to resonate with the inductance of the conductors thus eliminating the extra, external capacitance heretofore believed necessary for strip line circulators.

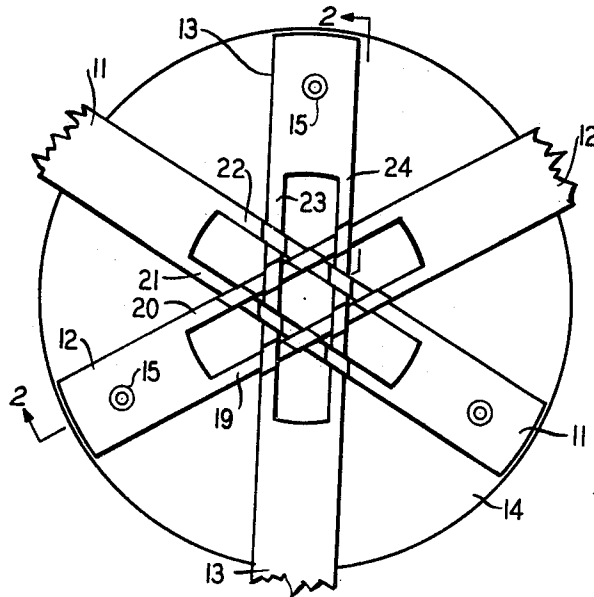


FIG. 1

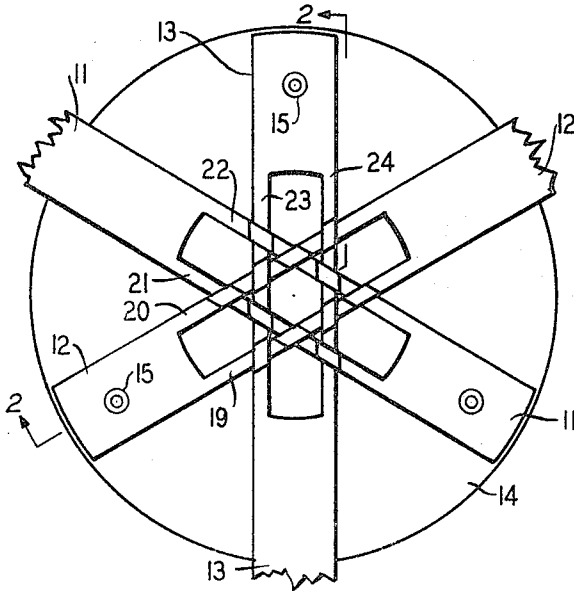


FIG. 2

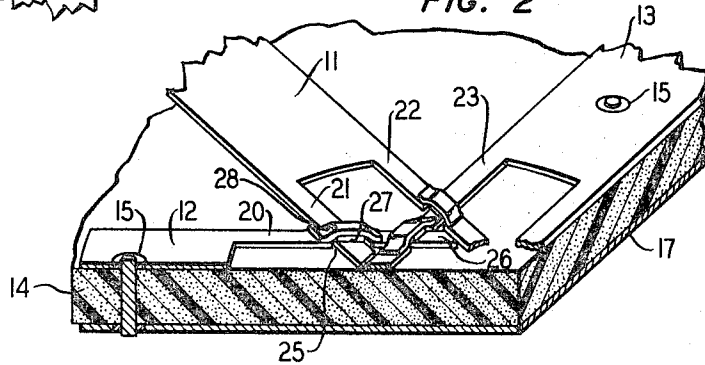


FIG. 3

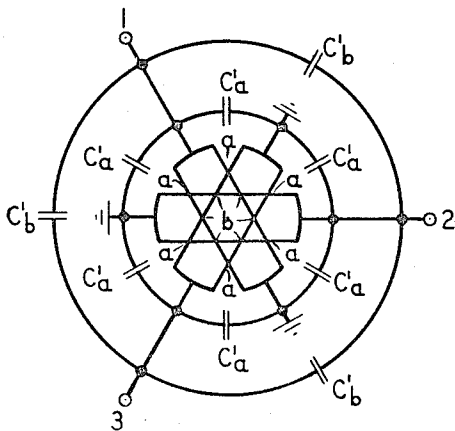


FIG. 4B

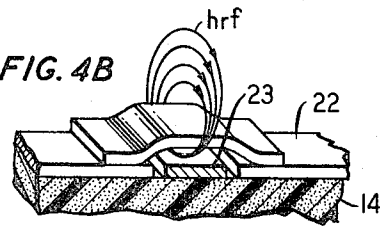
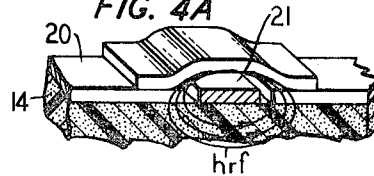


FIG. 4A



INVENTOR  
 R. H. KNERR  
 BY *Ray M. Porter, Jr.*

ATTORNEY

**THIN FILM Y-JUNCTION CIRCULATOR**

The present invention is a continuation-in-part of my application Ser. No. 795,907, filed Feb. 3, 1969, now U.S. Pat. No. 3,538,459 and relates to a new form of Y-junction circulator adapted to photolithographic construction techniques to reduce the overall size of the lumped element circulator and extend its range of applicability into higher regions of the microwave spectrum.

**BACKGROUND OF THE INVENTION**

A common form of the Y-junction circulator consists of a core of gyromagnetic material such as ferrite and a distributed constant resonator or center conductor. The dimensions of the center conductor are inversely proportional to the operating frequency of the circulator. With a disc-shaped resonator, for example, the diameter of the center conductor must be approximately equal to one-half the wavelength of the exciting signal, and if the frequency of the signal is halved, the diameter of the resonator must be doubled.

The prior art form of lumped element circulator, on the other hand, does not rely on dimensional resonance. In this form, which has been treated analytically in articles by Deutsch and Wieser, IEEE Transactions on Magnetics, Vol. 2, No. 3, Sept. 1966, pp. 278—282, and Konishi, IEEE Transactions on Microwave Theory and Techniques, Vol. 13, No. 6, Nov. 1965, pp. 852—864, and disclosed in U.S. Pats. to Roberts: No. 3,286,201, and Konishi: No. 3,335,374, the resonator includes a ferrite disc core and three tuned circuits, each containing a conductor and a discrete capacitive element. The conductors are radially disposed on the top surface of the core, with one end grounded in a manner provided three-fold symmetry. When connected to sources of high-frequency energy, these conductors exhibit inductive reactances; therefore, the discrete capacitors are added to each circuit to achieve the resonance necessary for flux induction in the core.

As is the case with the distributed constant form, the size of the lumped element circulator is substantially determined by its operating frequency, since the size of the discrete lumped inductive and capacitive elements decreases with decreasing wavelength. Though both circulator forms are frequency dependent, over a range of frequencies extending well into the gigahertz region, the lumped element circulator is more compact than a distributed constant circulator operating at the same frequency.

At the present time, extensive effort is being made in the art to combine, make smaller and reduce the cost of microwave components. It is particularly desirable, therefore, to achieve a practical lumped element circulator in the range at and above L-band which is more compact than the dimensionally resonant, distributed constant form.

**SUMMARY OF THE INVENTION**

The present invention concerns a new form of lumped element circulator in which the discrete reactances of the lumped element approach are combined into an integrated member analogous to the center conductor of the distributed constant form. The resulting integrated lumped element circulator, designed to be produced by photolithographic techniques, is reduced in size over both of the prior art forms, and offers lower cost, more opportunity for integration, and a range of operation extending well into the gigahertz region of the microwave spectrum.

The present invention is concerned with a circulator of the type in which each branch conductor is split into at least two strip conductors which intermesh with each other to produce a plurality of crossovers. In accordance with the present invention, the capacitance required to resonate each strip is produced in this circulator by reducing the electrical spacing at each crossing, thus increasing the capacitance at each crossing. Since half of the resulting capacitors essentially produce capacitance to ground while the other half essentially produce capacitance from port to port, it is important that a

particular pattern of overcrossings and undercrossings be maintained in order to maintain symmetry for various currents, voltages and impedances including the displacement currents through all capacitors. Lack of symmetry in these parameters stems directly from the difference of the radio frequency magnetic fields in the gyromagnetic material as produced by an overcrossing as opposed to an undercrossing. The required spacing and complicated pattern of the crossovers and crossunders are made possible by the thin film techniques to be described.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a diagrammatic representation of one embodiment of the present invention;

FIG. 2 is a sectional perspective view taken along the line 2-2 in FIG. 1;

FIG. 3 is a schematic diagram showing the equivalent capacitance approximating the capacitance associated with each of the crossings; and

FIGS. 4A and 4B are diagrammatic representations of details of the structure of FIG. 1.

**DETAILED DESCRIPTION**

Referring to FIGS. 1 and 2, the circulator components include three conductors 11, 12 and 13, arranged in rotational symmetry on the upper face of substrate 14. The substrate is composed of a gyromagnetic material, commonly a ferrite or a composite alumina-ferrite. The middle segment of each conductor is divided into at least two split conductors, such as 19 and 20 of strip 12, or 21 and 22 of strip 11, or 23 and 24 of strip 13, and the insulated crossing points of these split conductors are arranged as shown in FIG. 1 to induce a more uniform RF magnetic field inside the gyromagnetic material. More particularly, the desired pattern is preferably formed upon the ferrite substrate 20 by thin film, photolithographic processes well known in the art of printed circuits which involve applying a thin conductive layer of gold and a bonding layer such as titanium to the substrate, covering this conductive layer with photographically sensitive material the exposure of which affects its tolerance to chemical etching solutions, and etching the desired pattern after the pattern has been optically transferred to the sensitive layer from an appropriate photographic mask. A similar technique can lay down a pattern of dielectric material. Multiple overlays of conductive and dielectric layers can be formed by an appropriate series of masks.

Thus, a first pattern is applied which includes the main portion and two parallel strips of the split portion for each of the three conductors 11, 12 and 13. Each strip portion such as 20 has gaps such as 25 at the points at which that strip is to form an overcrossing with strip 21 and is continuous as at 26 where it is to form an undercrossing with strip 23. Each undercrossing strip is then covered at the crossing by a thin layer of nonconducting or dielectric material such as layer 27 over strip 21. Conductive material such as 28 is then applied over the dielectric 27, making a conductive bridge having conductive contact with each of the ends of strip 20 on either side of gap 25 and completing the insulated overcrossing of strip 20 over strip 21.

The circulator is completed by conductive probes 15 which connect one end of each conductor to ground plane 17 located beneath substrate 14 so that the conductors are arranged with their grounded ends 120° apart. Each grounded end is flanked by two ungrounded ends which comprise the input and output ports to the circulator. When any one of these ungrounded ports is excited by high-frequency wave energy, it will simultaneously excite both strips into which the conductor is split. A biasing magnetic field represented schematically by the vector  $H_{DC}$  is applied normal to the plane of the strips.

The capacity at any crossing is determined by the opposing areas  $F$  of the faces of the strips, their spacing  $\Phi$  and the

dielectric constant  $\epsilon$  of the interposed layer in accordance with the relation

$$C = 8.854 \times 10^{-12} \frac{\epsilon F}{l}$$

Typical parameters for a circulator operating in the 1.35 gigahertz (L-band) include a thickness for the conductive strips and overcrossings in the order of 17 or 18 microns, a dielectric constant  $\epsilon$  for the material of the layer such as 27 of approximately 3.5 and a thickness  $\Phi$  thereof no greater than 8 microns, a crossing area  $F$  of  $25 \times 10^4$  square microns. Such dimensions produce a capacitance  $C$  of approximately 1 picofarad per crossing. Considerable variation in these parameters is possible. For example, materials of appreciably higher dielectric constant can be used, and it is easily possible within the capability of known techniques to reduce the spacing  $\Phi$  by at least a factor of five. Scaling these parameters to the 200 megahertz range (UFH) would require a capacitance  $C$  per crossing of 15 picofarads obtained with an area  $F$  of 1 square millimeter and a spacing  $\Phi$  of 2 microns for a dielectric constant  $\epsilon$  of 3.5.

In accordance with the invention the capacity in the crossings comprises the sole resonating capacity of the circulator. In contrast to prior art structures where the capacity of similar crossings was intentionally minimized and then ignored as negligible at the frequency under consideration, the capacity of the crossing in accordance with the invention is intentionally increased and has a significant magnitude at the operating frequency. Whereas in the prior art it made no difference whether the location of the crossing producing the capacity was above or below a given strip so long as the rotational symmetry of the strips themselves was maintained, it is essential to the present invention that symmetry of the pattern of overcrossing and undercrossing be maintained as well. The significance of this symmetry requirement will be appreciated when it is recognized that if a driven strip such as 21 undercrosses an undriven or grounded strip such as 20, the radio frequency magnetic field lines  $h_r$  around the driven strip close within and are affected by the ferrite substrate 14 as shown in FIG. 4A. If the driven strip such as 22 overcrosses the grounded strip such as 23 the lines close entirely outside of ferrite 14. Thus, an overcrossing has significantly different inductance, voltage drop, and therefore, displacement current through the crossing capacitance from those of an undercrossing. It is a feature of the invention that concomitantly with making the crossing capacitance significant at the operating frequency, the pattern of overcrossing and undercrossing is made identical for each strip so as to prevent the displacement currents through the capacitance from disturbing the three-fold symmetry of the structure. More particularly, every right-hand strip of each pair when viewed from either the grounded or ungrounded end has alternate undercrossings and overcrossings each starting with an undercrossing. Each left hand strip starts with an overcrossing. The resulting equivalent circuit is shown in FIG. 3. The capacitors of each of the six outer crossings  $a$  can be transformed into six capacitors  $C_a'$  between each port and ground. The capacitors of each of the six inner crossings  $b$  can be approximately transformed into three capacitors  $C_b'$  between adjacent input ports.

When the pattern of symmetry specified above is maintained, capacitor  $C_a$  and  $C_b$  tune with the inductive reactance of each of the strips to produce the resonance required for circulator action. Since the need for and effect of this resonance is fully developed in the prior art cited above, further analysis is not here required. The entire capacitance required is supplied by the crossing capacitance and no extra, external, lumped constant capacitors are required as in the prior art.

It should be noted that the pattern of overcrossing and undercrossing shown in FIG. 1 could be exactly reversed, i.e., every overcrossing would become an undercrossing and vice

versa. While applicant does not necessarily wish to be limited to these two patterns of symmetry, it should be noted that no other pattern has been identified which has sufficient degrees of symmetry including displacement current symmetry through the crossing capacitors to operate as a circulator in accordance with the invention without external capacitors.

I claim:

1. A circulator for operation in a given band of high-frequency electromagnetic wave energy comprising:
  - a substrate of gyromagnetic material;
  - a plurality of flat conductive strips arranged in groups with the strips of each group extending parallel to each other across said substrate and strips of different groups intermeshing at  $120^\circ$  to each other across said substrate;
  - each of said strips forming a part of a strip transmission line and exhibiting an inductive reactance when one end of all strips within a group is excited by high-frequency wave energy, each strip having an overcrossing and an undercrossing with every strip of other groups at points adjacent to said substrate; and
  - the pattern of said over and undercrossings being identical for every strip so that the capacitances between strips at said crossings together resonate with the inductive reactance of the strips within said given band.
2. The combination according to claim 1 wherein each of said strips have two overcrossings and two undercrossings.
3. The combination according to claim 1 wherein strips of the same group have opposite sequences of undercrossings and overcrossings.
4. The combination according to claim 1 wherein the capacitances at said crossings comprise substantially the sole capacitance resonating with said inductive reactance.
5. The combination according to claim 1 wherein the spacing between faces of strips at a crossing is no greater than 8 microns.
6. A Y-junction circulator comprising:
  - a ground plane;
  - a core of gyromagnetic material located above the ground plane;
  - three substantially flat conducting members located above the gyromagnetic core, each of the members exhibiting an inductive reactance when one end thereof is connected to a source of high-frequency energy, the middle segment of each member being divided into a plurality of substantially flat parallel inner conductors, the members being radially arranged  $120^\circ$  apart with the grounded end of each member lying between the ungrounded ends of the other members and each inner conductor of a first member crossing the inner conductors of the other members; and
  - means for closely spacing pairs of inner conductors at their respective crossing points to produce capacitances at the crossing points sufficient to resonate with the inductive reactance of the members at a desired high frequency of operation.
7. A Y-junction circulator comprising:
  - a lower ground plane having a central axis;
  - three coplanar conductors, each having one end grounded, radially arranged in rotational symmetry about the central axis above the ground plane so that their midpoints lie on the axis, their middle portions overlap, and the grounded end of a first conductor lies between the ungrounded ends of the second and third conductors;
  - a member of gyromagnetic material located between the ground plane and the conductors;
  - and means for symmetrically producing a significant capacitance associated with the overlapping of each conductor, said means comprising the sole significant capacitance forming a resonant circuit with the inductance of said conductors.