Ferrite-Superconductor Devices for Advanced Microwave Applications

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***Abstract*—Microwave devices comprising magnetized ferrite in contact with superconductor circuits designed to eliminate magnetic field penetration of the superconductor have demonstrated phase shift without significant conduction losses. The device structures are adaptable to low- or high-T_C superconductors. A nonoptimized design of a ferrite phase shifter that employs niobium or YBCO meanderlines has produced over 1000 degrees of differential phase shift with a figure of merit exceeding 1000 degrees/dB at X band. By combining superconductor meanderline sections with alternating T junctions on a ferrite substrate in a configuration with three-fold symmetry, a low-loss three-port switching circulator has been demonstrated.**

I. Introduction

Since their discovery in 1986, a main thrust in the development of high-T_c superconductors has been for electronic applications. As a consequence, emphasis on microwave applications at $T = 77$ K (the boiling point of liquid nitrogen) has grown steadily as surface resistances have improved with refinement of thin-film deposition techniques. Recent films of YBCO have featured surface resistances superior to that of cold conventional copper at frequencies ω extending above 100 GHz [1], with the advantage to the superconductor increasing by a factor of $\omega^{-3/2}$ as the frequency decreases into the microwave bands.

Small, lightweight, low-loss microwave phase shifters have been of continuing interest for investigating the systems advantages of subarray architecture for phased array radars that would operate from ground-based, airborne, or space-based platforms. Low-loss switching circulators for filter-bank selection is another important application to modern microwave systems. A potentially attractive technology for this purpose could be ferrite devices in a monolithic geometry that permits the use of high-T_c superconductor circuits patterned from epitaxial films to eliminate the normally significant conduction losses obtained with copper circuits. With low-loss superconductors, miniature devices based on microstrip circuitry can become attractive replacements for bulky waveguide systems, while offering dramatically improved figures of merit (FOM).

The conventional technology that utilizes dispersive properties of ferrite has been a vital part of microwave systems. One major source of losses in these devices, particularly in microstrip and stripline geometries, is the electrical resistance of the conductor circuits, which are usually copper or gold. Because of the deterioration of superconductor surface resistances by magnetic fields [2], however, the use of cryo-cooled superconductors to solve the conduction loss problem has not been an attractive option. For designs where significant magnetic fields penetrate the circuit [3], superconductivity may have no advantage over the normal conductivity of copper at 77 K.

To place this discussion of loss in a broader context, it is useful to recall that insertion losses in ferrite devices are also determined by ferrimagnetic relaxation and polaronic conductivity in the ferrite, commonly referred to as "magnetic" and "dielectric" loss, respectively. Another consideration that is important at millimeter wavelengths is the signal path length, which is prevented from being shortened in proportion to the reduced wavelengths because of the limited saturation magnetizations (maximum $4\pi M_s \approx 5000$ G) of ferrites at room temperature. At cryogenic temperatures, the $4\pi M_s$ values can increase dramatically and device insertion losses due to electrical conduction may be virtually eliminated through the use of superconductors. Our experiments to establish the feasibility of ferrite microstrip/stripline phase shifting devices that utilize the low losses of superconductors have indicated that it should be possible to design ferrite-superconductor (FSC) devices that operate with reduced ferrite losses and virtually no conduction losses in the microwave frequency bands.

II. Device Principles

Ferrite devices that employ superconductor circuits are the same as those that are used conventionally at room temperature. The fundamental concern that arises when the two technologies are merged stems from the sensitivity of the superconductor to magnetic fields.

A. Gyromagnetic Effects

The basic interaction that creates dispersive effects on r.f. waves in ferrimagnetic media is gyromagnetic. From the classical analysis of a magnetic moment (or magnetization) M precessing about a magnetic field vector H, relations for the complex permeability $\mu = \mu' - j\mu''$ that enters into the determination of the r.f. wave propagation constant [4] were derived. For linear polarization the r.f. wave undergoes Faraday rotation; for circular polarization, nonreciprocal phase shift effects occur. In this discussion, the focus will be on

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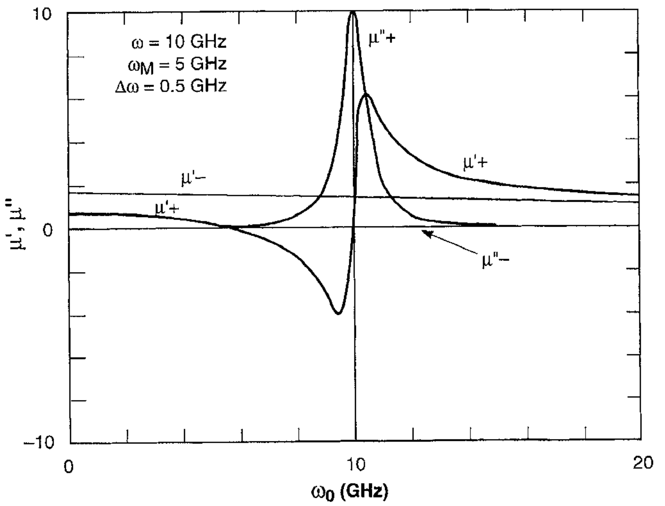


Fig. 1. Variation of complex permeability components for circular polarization as a function of ferrimagnetic resonance frequency ω_0 for a ferrite with $\omega_M = 5$ GHz and $\Delta\omega = 0.5$ GHz. The device operating frequency $\omega = 10$ GHz. Notice that $\mu'_+ - \mu'_-$ is greater and less frequency sensitive in the regime where $\omega_0 \ll \omega$.

the use of circular polarization for maximum phase shift. The permeability relations are:

$$\mu'_\pm = 1 + \left[\frac{\omega_M(\omega_0 \mp \omega)}{(\omega_0 \mp \omega)^2 + (\Delta\omega)^2}\right] \tag{1}$$

$$\mu''_\pm = \left[\frac{\omega_M \Delta\omega}{(\omega_0 \mp \omega)^2 + (\Delta\omega)^2}\right] \tag{2}$$

where the gyromagnetic constant $\gamma = 2.8$ GHz/kOe, ferrimagnetic resonance frequency $\omega_0 = \gamma H$, $\omega_M = \gamma(4\ \pi M)$, and $\Delta\omega$ is the half-linewidth. The $\pm$ subscript symbol refers to the two oppositely rotating senses of circular polarization about the direction of propagation. According to (1) and (2), at a given frequency, there are two ways to alter μ: by varying ω_0 through manipulation of the external field H, or by changing ω_M through adjustment of the magnetization.

The basic principle on which devices are designed is to optimize the phase shift $\phi \sim (\mu')^{1/2}$ and minimize the absorption loss, the magnetic component of which is determined by $\tan\delta_\mu \sim \mu''/\mu'$. Therefore, with the exception of certain devices where the rapid variations of μ *vs.* applied field H can be exploited to provide sensitive tuning, the application of an external field is not used. Fig. 1 shows that the difference between μ'_+ and μ'_- offers the opportunity to take advantage of a greater phase shift $\Delta\phi = \phi_+ - \phi_-$, referred to as the differential phase shift, that is achieved by switching the magnetization of the ferrite between opposing states of magnetization in the amount desired. For these situations the devices operate far from resonance, i.e., $\omega_0 \ll \omega$, and relations for nonreciprocal phase shift and magnetic absorption loss may be approximated from (1) and (2):

$$\Delta\phi \sim \omega_M/\omega \tag{3}$$

and

$$\tan\delta_\mu \sim \Delta\omega/\omega. \tag{4}$$

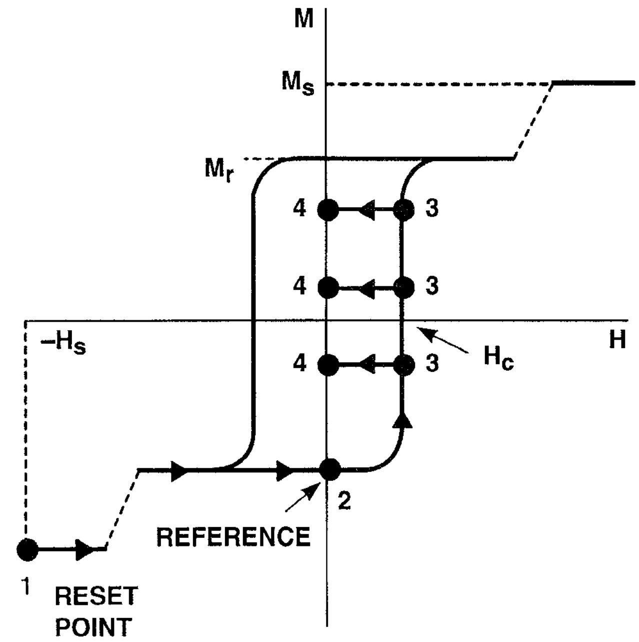


Fig. 2. Hysteresis loop principle for flux drive switching of microwave phase shifters.

The design objective therefore is to employ the ferrite with largest $4\pi M$ and the narrowest $\Delta\omega$. There is a limitation on the values of $4\pi M$, however, that arise from the magnetic fields that occur among the domains in partially magnetized ferrite. The magnitude of these fields range from 0 to $4\pi M$ and create absorption losses over the frequency band from 0 to $\gamma 4\ \pi M$. Since this "low-field" loss regime must be avoided for devices, the ferrite selected for a particular application requires a $4\pi M$ value low enough to allow operation in the desired frequency band. For most applications, $\omega_M/\omega \approx 0.5$ is a desirable ratio. A point worth noting is that the maximum useful $4\pi M$ of microwave quality ferrites is approximately 5000 G. This means that for $\omega > 25$ GHz, the efficiency of the ferrite will begin to deteriorate because ferrite path lengths can no longer be shortened in proportion to wavelength by simply raising $4\pi M$ to an appropriate value. At cryogenic temperatures, however, $4\pi M$ values can be increased to values almost double those at room temperature. Examples of this effect will be evident in the data presented later.

B. Phase Shift Control

For typical phase shifters and junction circulators, the value of ϕ is controlled by the parameter ω_M, which in turn is established by the device's operating point on the ferrite hysteresis loop. In switching applications where remanent-state phase shifters are employed in phase array radars, the design of the hysteresis loop is of critical importance. The key features of the ferrite hysteresis loop illustrated in Fig. 2 are therefore its remanence ratio (the ratio of the remanent magnetization to the saturation magnetization M_r/M_s, which is typically 0.75), and its coercive field H_c which should be as small as possible to ensure low switching energies and switching times, while maintaining high remanence ratio.

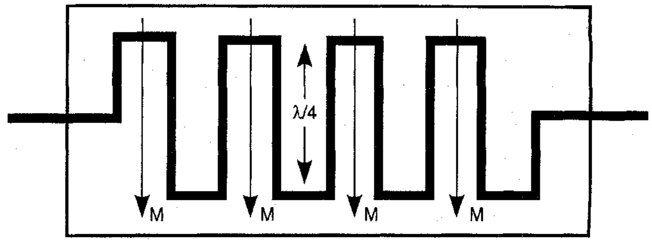
The phase shift value is directly proportional to $4\pi M$ which is varied by techniques that establish selected states of partial magnetization through the use of energy pulses to generate controlled amounts of magnetic flux reversal. An abbreviated relation [5] to describe this flux drive method is given by

$$\Delta\psi \approx \int_0^\tau V \cdot dt \tag{5}$$

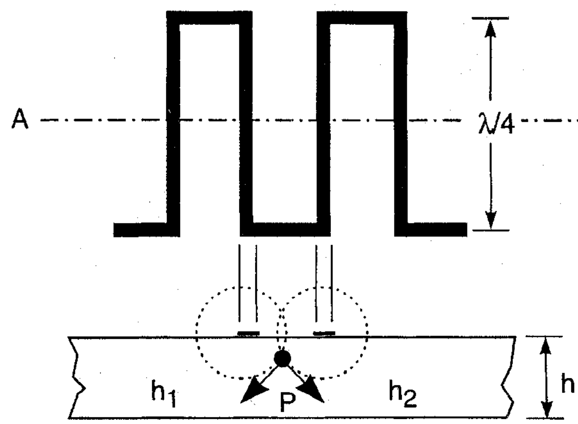
where the flux increment $\Delta\psi$ is set by the driver pulse. If the ferrite is first set to remanence $-4\pi M_r$ on its major hysteresis loop by applying a saturating pulse of field $-H_s$ (point 1 of Fig. 2) and allowing the magnetization to relax to its maximum remanence value (point 2, the latching condition), various smaller positive pulses of defined voltage V and duration τ will bring the magnetization to points 3 on a minor loop by reversing predeterimined amounts of flux $\Delta\psi$. The magnetization then attains the corresponding new remanent states (point 4) after each pulse is completed. This procedure may be followed to obtain any value of $\Delta\psi$ within the range available to the device. By resetting to point 2 before each new pulse is applied, the full range of nonreciprocal differential phase shift $\Delta\phi$ may be exploited. As indicated, the linearity of the relation between $\Delta\phi$ and $\Delta\psi$ is highly dependent on the shape of the hysteresis loop.

C. Superconductor Circuitry

To combine a ferrite in its magnetized state with a superconductor without allowing magnetic fields to penetrate the superconductor and degrade its properties, we used a design based on magnetic flux confinement within a closed magnetic circuit, e.g., ferrite in a toroidal geometry, to satisfy the geometric requirement [6]–[8]. In effect there are no magnetic poles (i.e., no divergence of magnetization) to produce an external *H* field. To accomplish this result, the superconductor may be in contact with any surface of the magnetized toroid. The only other basic requirement is for the RF magnetic field to be normal to the magnetization of the ferrite. For circular polarization, which is obtained by combining two linearly polarized waves separated in phase by 90 degrees a meanderline structure is used. The relationships between ferrite magnetization, meander design, and resulting r.f. magnetic fields are shown in Fig. 3.



(a)



(b)

Fig. 3. Meanderline structure showing the generation of circular polarization.

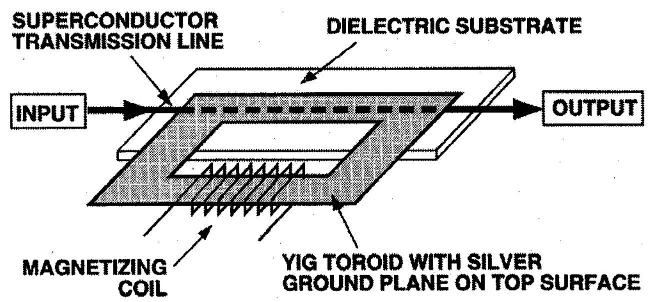


Fig. 4. Schematic view of reciprocal phase shifter showing the coupling relationship between ferrite and superconductor. Magnetic flux is confined within the ferrite toroid.

III. Phase Shifters

For optimum performance of devices comprising magnetized ferrites in proximity to superconductors magnetic flux invasion of the superconductor must be minimized. This can be achieved with designs based on flux confinement within closed magnetic paths. In early experiments [6] carried out at 4 K with a simple reciprocal phase shifter using a low-T_c superconductor, no increase in conduction loss was detected from a one-inch linear niobium (Nb) transmission line deposited on a sapphire (Al_2O_3) substrate and pressed in contact with one side of a magnetized planar "window-frame" YIG toroid, shown in Fig. 4. The essence of this concept is the confinement of dc magnetic flux within the ferrite, thereby avoiding external dc magnetic field penetration of the superconductor while permitting r.f. magnetic field penetration of the ferrite.

To demonstrate more clearly the potential of this technology, two experimental nonreciprocal phase shifters were constructed with meanderline circuits [9]–[11]. In the first version, shown in Fig. 5, the Nb circuit was deposited directly on the ferrite to optimize the interaction between microwave signal and ferrite. This configuration also simplifies the design and packaging, and will be suitable for circuits of high-T_c films when ferrimagnetic substrates can be used for epitaxial film deposition [12]. The second phase shifter, shown in Fig. 6, consisted of a Nb circuit deposited on a lanthanum aluminate ($LaAlO_3$) substrate. The Nb meanderline was formed on a $LaAlO_3$ substrate in order to duplicate as closely as possible the dielectric medium and electrical circuit design that will are approximate for high-T_c YBCO superconductor.

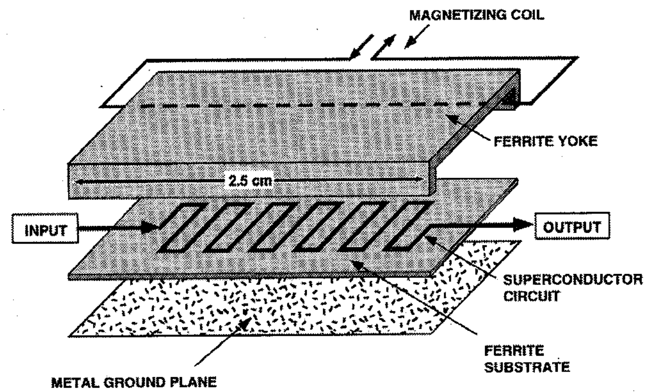


Fig. 5. Nonreciprocal differential phase shifter with meanderline superconductor deposited directly on ferrite. Magnetic flux is confined within ferrite toroidal structure.

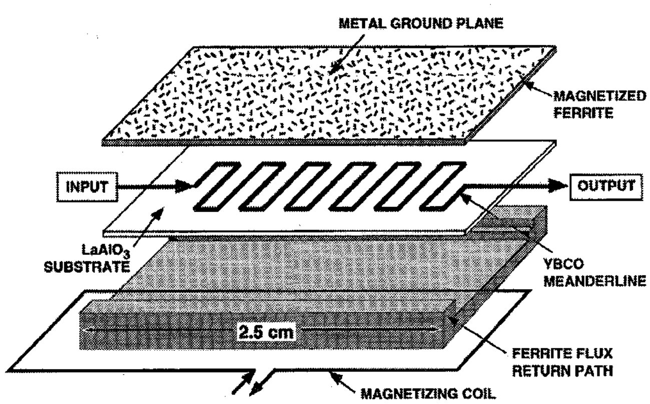


Fig. 6. Schematic view of layered phase shifter. Superconductor (Nb or YBCO) is deposited on $LaAlO_3$. The ferrite is held in close proximity to the YBCO meanderline.

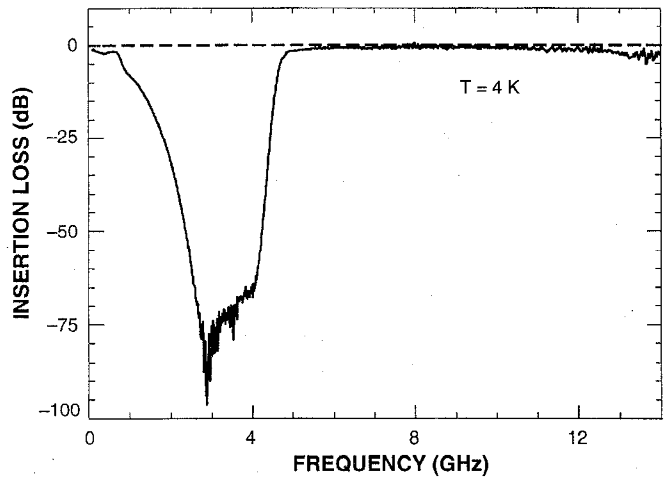


Fig. 7. Insertion loss versus frequency of Nb meanderline superconductor-on-ferrite phase shifter (fixture of Fig. 5). Loss due to reflection effects from test circuit impedance mismatches has not been subtracted.

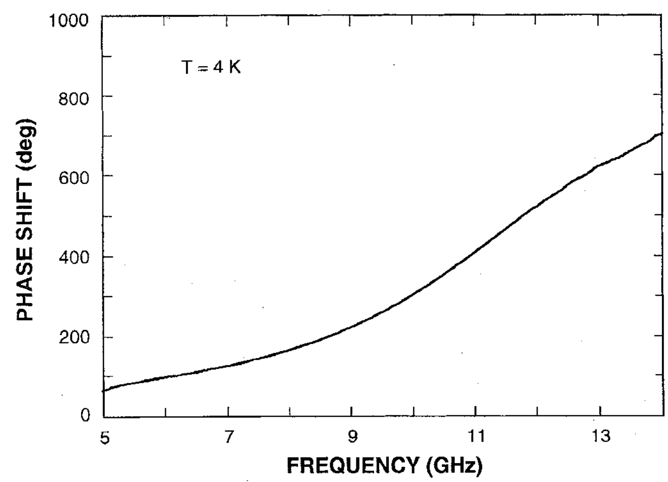


Fig. 8. Differential phase shift versus frequency from Nb meanderline circuit on ferrite substrate (fixture of Fig. 5). Data indicate nonoptimized meanderline design, with peak above 14 GHz.

These device configurations are based on layered arrangements in which the ferrite magnetic circuit is composed of two parts. When the ferrite parts are combined, they take the form of a rectangular toroid that completes the magnetic circuit and establishes the collinearity of the magnetization direction with the meanders. The magnetization reversal necessary for the measurement of differential phase shift is accomplished through dc current switching in the magnetizing coil. With both Nb meanderline circuit devices, results of insertion loss and differential phase shift measurements confirmed that the principle of operation is valid. Measured insertion loss for the device of Fig. 5 is shown in Fig. 7. The low-field loss regime at frequency $\omega < 5$ GHz was caused by the interaction between the microwave signal and the partially magnetized ferrite [13], [14] through ferrimagnetic resonance up to $\omega_M = \gamma 4\pi M$. Subtraction of reflection losses revealed absorption losses <0.3 dB between 9 and 12 GHz for differential phase shift from 200 to 500 degrees (Fig. 8), thereby producing an intrinsic FOM greater than 1000 degrees/dB over most of this frequency range.

Fig. 9 presents differential phase shift data for the device of Fig. 6 with ferrite of $4\pi M = 1200$ Gauss (300 K value) and with $LaAlO_3$ as the substrate for a substantially longer Nb circuit. A peak phase shift of 2400 degrees occurs at 9.5 GHz for the ferrite in the magnetically saturated state, and 1400 degrees in the remanent state. The transmission performance of this device was partially marred by impedance mismatches, but the absorption loss after corrections for reflection losses was less than 1 dB in the frequency range of interest. The difference in phase shift characteristics between the two device configurations is the result of the dielectric environments surrounding the superconductor circuits. In Fig. 10 the transmission loss and differential phase shift at 77 K for a YBCO circuit deposited on a $LaAlO_3$ substrate in the device configuration of Fig. 6 reveals performance comparable to that of the Nb circuit at 4 K. The photo in Fig. 11 shows a prototype device with inverted $LaAlO_3$ substrate held in contact with the ferrite by means of "spring fingers."

The FOM values obtained in these experiments may be compared with the 130 degrees/dB value (at remanence) at X band reported by Roome [15] with a copper meanderline circuit at room temperature. This value is almost an order of magnitude worse than that of the superconductor device reported here. Even at cryogenic temperatures, where the

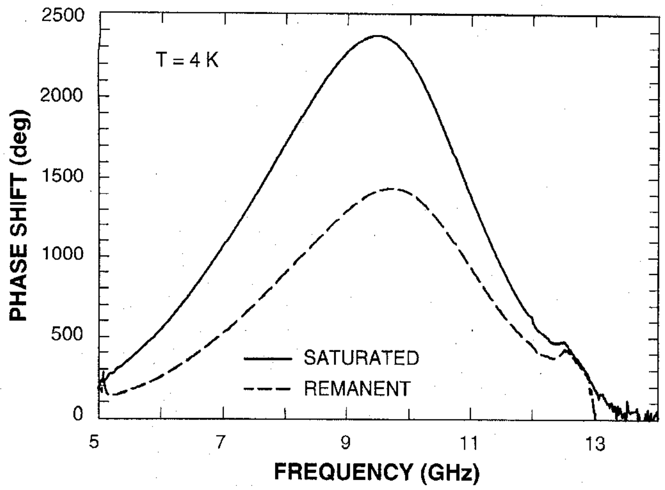


Fig. 9. Differential phase shift versus frequency from Nb meanderline circuit on $LaAlO_3$ substrate (fixture of Fig. 6). Curves for saturated and remanent states are shown.

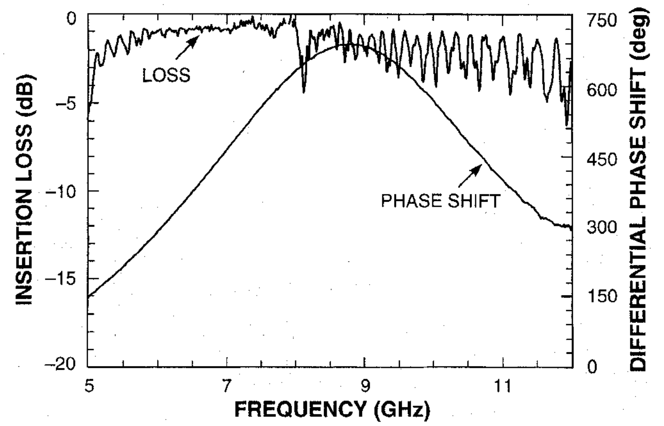


Fig. 10. Insertion loss and differential phase shift versus frequency from YBCO meanderline circuit on $LaAlO_3$ substrate (fixture of Fig. 6).

insertion loss from the copper circuit of Roome's device would decrease by less than a factor of two, the device employing superconductors would have at least a factor-of-five improvement in FOM. If the theoretical limits of the ferrite properties can be realized in practice, an optimized design with ideal impedance matching of the superconductor circuit and full utilization of $4\pi M$, FOM values approaching 10 000 degrees/dB could be a realistic goal.

For miniaturizing of device dimensions and optimization of the magnetic circuit integrity, a planar structure based on the generic type sketched in Fig. 12 has been fabricated and tested. Initial results are comparable to those reported for the two-part ferrite structures. This is a structure that still confines the magnetic flux entirely to the ferrite but eliminates the added external yoke. The return path of the flux is outside of the meanderline so that magnetically the device functions identically to the examples shown in Fig. 5 and 6. In addition to reduced size and weight this planar geometry is directly usable with compact structures in which the superconductor is deposited directly on the ferrite or the ferrite is deposited as a thin or thick film on a suitable substrate. Fig. 13 shows the results with the in-plane magnetic circuit.

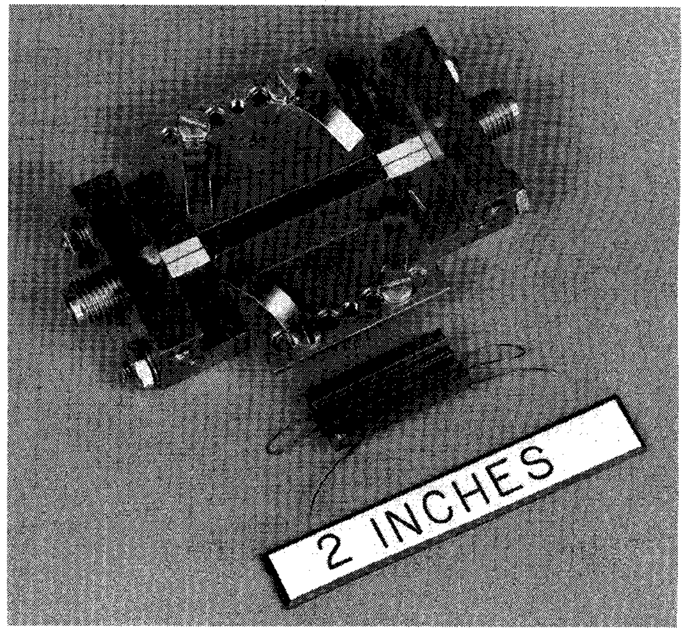


Fig. 11. Photograph of YBCO meanderline phase shifter on $LaAlO_3$ substrate. The ferrite yoke has been removed to reveal the meanderline structure.

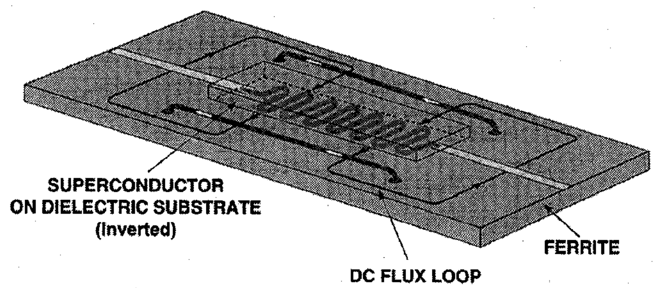


Fig. 12. Schematic of a generic planar meanderline phase shifter to minimize size and weight and to eliminate air gaps in the magnetic flux path.

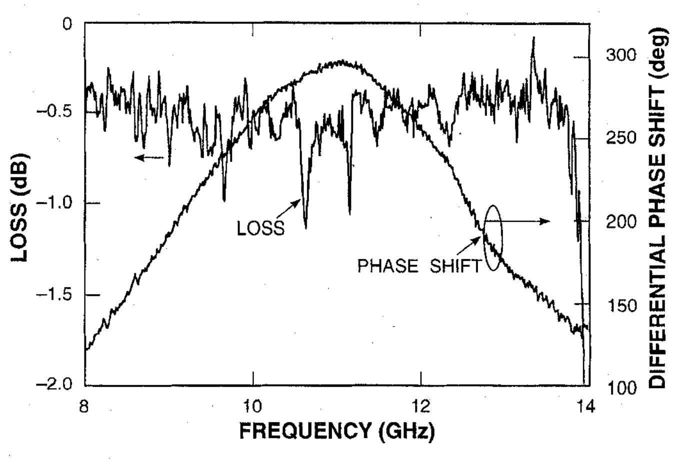


Fig. 13. Example of insertion loss and differential phase shift versus frequency from YBCO meanderline circuit on $LaAlO_3$ substrate with fixture based on Fig. 12. Excessive ripples in the loss curve are the result of long-line effects and impedance mismatches.

IV. CIRCULATORS/SWITCHES

The principles of magnetic and cryogenic design described above for the FSC phase shifter may also be applied to a three-port circulator. A style of circulator design which is

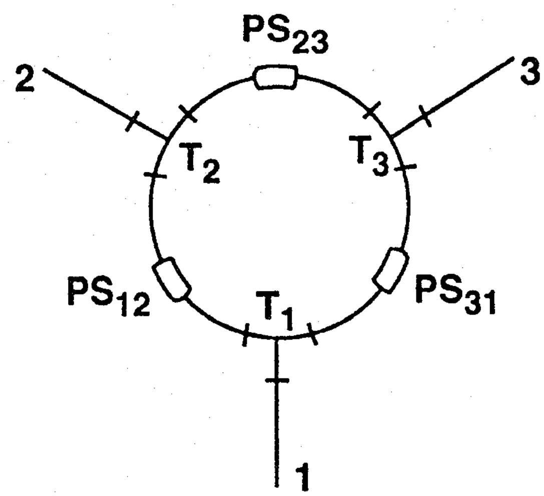
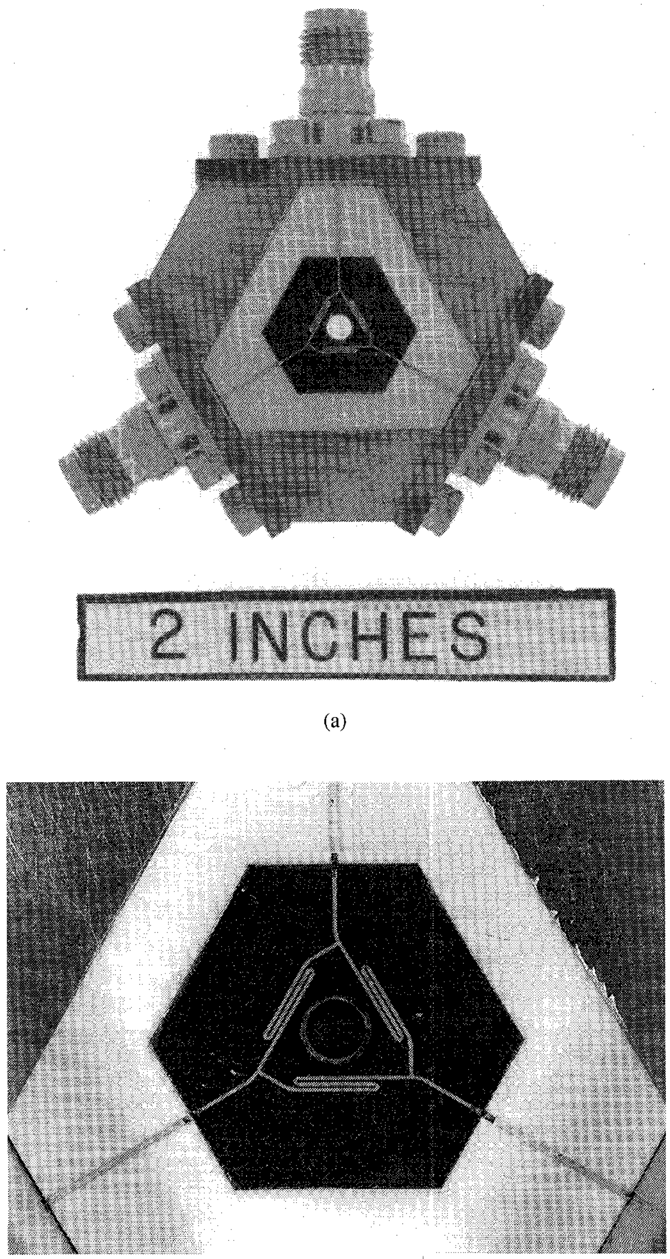


Fig. 14. Schematic diagram of ring network. T and PS denote, respectively, symmetrical T junctions and nonreciprocal phase shifters.

well adapted to planar circuits and more especially to ferrite-superconductor technology is the ring-network circulator. The concept was introduced in 1965 [16] and was the subject of experimental investigation at that time [17]. The specific embodiment was a ring composed of three identical nonreciprocal phase shifters alternating with three identical reciprocal T junctions, constituting a three-port junction circulator, as shown schematically in Fig. 14. This design principle is particularly applicable to miniature planar circuit design, including the FSC combination of superconducting circuit path and planar magnetic flux confinement, but the formulation is general and valid for any type of microwave or millimeter-wave transmission medium.

The analysis of the device [18], [19] is based upon a rigorous scattering formulation of clockwise- and counterclockwise-propagating partial waves. It leads to characterization of the nonreciprocal phase shift in relation to the T junction scattering parameters such that, assembled into a ring, the network satisfies the imposed condition of perfect circulation. Circulator performance over the frequency range in that vicinity is governed by the dispersive characteristics of the components. The results of computations indicate that, by suitable design, the required magnitude of differential phase shift may be made small, so as to minimize the gyrotropic interaction needed. Further, by appropriate choice of dispersive characteristics as specified by the theory, for example by incorporating reactive elements at the T junctions, broadband performance may be achieved.

Early versions of the meander line ring-network circulators are shown in the photographs of Fig. 15. In the illustrated version, the circuit is gold, but a superconductor would be substituted for cryogenic operation. A central hole in the substrate creates the toriodal geometry for flux confinement and accommodates coil windings for establishing and reversing the state of magnetization. The experimental model shown is narrow band; results at 77 K give insertion loss below 1 dB and isolation greater than 15 dB over a 2% band. In Fig. 16, comparable results are presented for a device of the same design but with a niobium circuit, cooled to 4 K.



(a)

(b)

Fig. 15. Photographs of a ring network circulator: (a) laboratory prototype microstrip circulator with ferrite substrate and meanderline nonreciprocal phase shifters; (b) enlarged view of the ring network.

This class of designs confers numerous potential benefits. In contrast to the conventional resonant-type junction circulator for which the ferrite element must be magnetized in the direction normal to the plane of the circuit by means of an external magnetic yoke, which would degrade the performance of the superconductor [3], the ring- network circulator lends itself naturally to magnetization in the plane of the substrate. Such a configuration has significant advantages in reduction of size, weight, complexity, and energy consumption of the magnetizing structure. Further, it allows for reduced coercivity requirements in self-magnetized versions (having no external magnet structure) as well as for high-speed, energy-efficient switching capability in reversible versions of the circulator

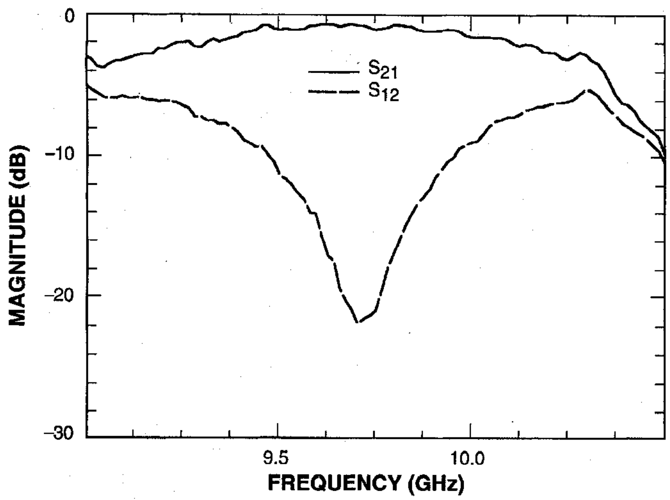


Fig. 16. Insertion loss (S_{21}) and isolation (S_{12}) versus frequency measured at 4 K from a ring network circulator with a Nb meanderline circuit on a ferrite substrate.

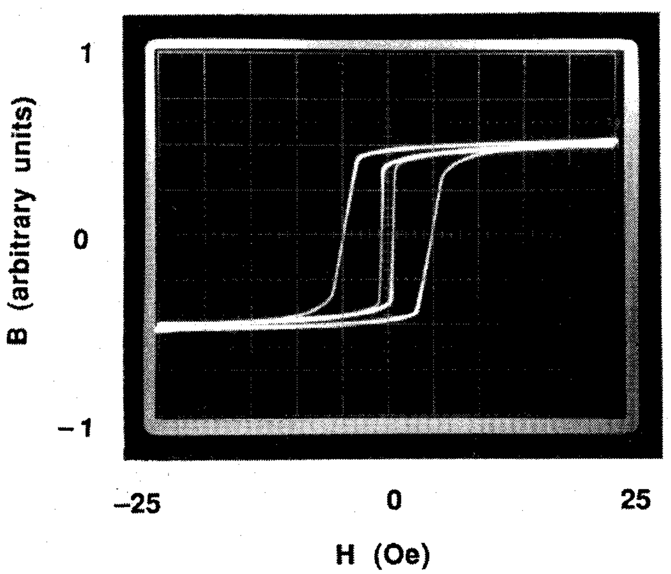


Fig. 17. Enlargement of YIG hysteresis loop area for a decrease in T from 300 to 77 K. The coercive field increases by almost a factor of ten and an increase in magnetization is indicated by a 20% enhancement of the remanent point. The 77 K loop is not fully saturated at $H = 25$ Oe.

which may function very effectively as switches. The configuration provides means for achievement of the maximum benefit of low insertion loss when incorporating superconducting circuits.

V. Materials

The choice of ferrite for use at cryogenic temperatures is determined by the same considerations that apply at room temperature. Magnetization must be selected so that ω_M is sufficiently lower than the operating frequency ω that low-field loss is avoided. As shown by the hysteresis loops of YIG in Fig. 17, the decrease in temperature from 300 to 77 K causes more than a five-fold increase in the coercive field due to a rise in the magnetocrystalline anisotropy. For switching of the magnetic state with low energy consumption, alteration of the standard room temperature microwave ferrite compositions will be necessary to attain the highest efficiency. For latching operation, designs that employ a single-piece ferrite toroid may be required to avoid deterioration of the hysteresis loop squareness caused by gaps that occur where the two ferrite pieces are joined to form a closed path.

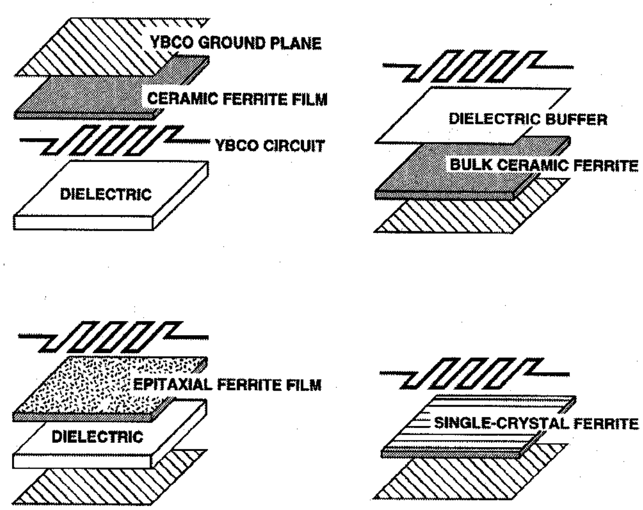


Fig. 18. Proposed arrangements for materials integration by layering of ferrites and high-T_c superconductors.

Another objective is to create the most intimate contact between ferrite and superconductor in order to maximize the interaction and to establish the highest possible reproducibility. In Fig. 18 four schemes are illustrated for achieving the desired layering. In each case, the YBCO (or equivalent) superconductor is grown in the closest proximity to the ferrite surface, which may in turn be magnetized with internal flux confinement.

VI. Discussion

The feasibility of employing superconductors in microwave ferrite devices without deterioration of the superconductor properties has been successfully demonstrated. This new technology offers not only dramatically improved efficiency for applications requiring modest powers, but also makes possible the use of compact lower cost microstrip structures to replace the bulky ferrite waveguide phase shifters.

To achieve low cost in phased-array radars, the choice of array configuration is generally decided on the basis of tradeoffs between performance and the totals of weight, size, power consumption, and cost. The order-of-magnitude advantages gained from the superior performance and reduced size and weight of the FSC technology can make it the preferred option, notwithstanding the added cost and complications of a cryogenic enclosure. For filter-bank selector applications that would employ the ring-network circulator device, these issues also apply, and may include even larger bandwidths and switching speeds. For implementation of the low-loss FSC phase shifters, circulator switches and other devices that utilize this low-loss principle, the adoption of cryogenically cooled array antennas is also an important step and should be treated as part of the system design where appropriate.

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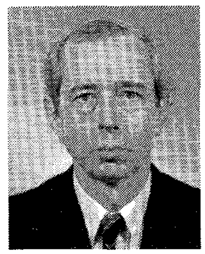

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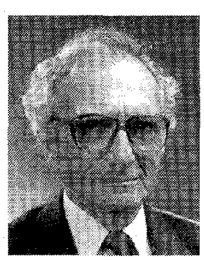

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