STATUS OF FERRITE TECHNOLOGY IN THE UNITED STATES

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ABSTRACT

Within the past few years there has been a resurgence of interest in the United States in developing ferrite technology for microwave applications. Emphasis has been on new material growth techniques, especially thin-film approaches, as well as improved device configurations. Although much of the activity has been directed toward developing ferrite components that are compatible with monolithic circuits, there has also been steady progress in advancing the state-of-the-art in high-power waveguide technology to support vacuum electronics based systems.

INTRODUCTION

Within the past several years there have been order-of-magnitude reductions in the cost and size of microwave circuits, the impetus being supplied by potential high volume applications in both the defense and commercial sectors. These advances have come about through a combination of improved design, fabrication and production techniques. However, this progress has largely been confined to components which can be readily implemented with semiconductor technology, specifically gallium-arsenide and related compounds and silicon. Advances in components which can best be implemented with ferrite technology, such as circulators and isolators, have been far less dramatic. However, efforts have been recently initiated in the United States to substantially reduce the cost and/or size of ferrite components to enable them to be more compatible with monolithic circuits. These efforts include improved hybrid designs as well as technology which is expected to lead to viable monolithic components.

In addition to this thrust in monolithic-compatible components, there continues to be progress in high power waveguide components to address the ever-escalating demands of DoD systems for higher powers, higher frequencies, wider bandwidths, etc. This paper highlights recent progress and trends in ferrite technology in the US with examples given relating to both types of applications.

MICROSTRIP/STRIPLINE COMPONENTS

Circulators

Circulators are by far the most widely used ferrite components since their non-reciprocal behavior cannot be readily duplicated by competing technology. The most common configuration is the Y-junction which is readily implemented in microstrip and stripline circuitry. Both commercial and defense sectors are striving for low cost, size and weight and these factors are driving many of the present technology programs. The most important of the emerging DoD applications is the separation of transmit and receive functions in solid-state active arrays. This is a highly demanding application since bandwidth is commonly wide (50-100%), size in both transverse dimensions must be commensurate with array spacing (≤ half-wavelength at the highest operating frequency), performance and unit-to-unit reproducibility must be high and cost must be a small fraction of the overall module cost (typically ~ $10 each including packaging and testing).

A recent example of a microstrip circulator built for a phased-array application is given in Table 1.(1) These units were fabricated via a ferrite-puck imbedded in an alumina substrate approach in a quasi-production environment, i.e. at rates of about 1000 per day and up to 22,000 per month. Unit to unit reproducibility was excellent; more than 90% had a relative VSWR of less than 1.05. Production cost was ~$10 per unit.

Table I. Microstrip Circulator
(Electromagnetic Sciences)

Frequency:	7 - 11 GHz
Insertion Loss:	0.35 dB
Isolation:	25 dB
Reflection Uniformity:	40 dB
Size:	0.33 x 0.15 x 0.8"
Weight:	12 g

Some future DoD active array systems will require extremely wide instantaneous bandwidths to fulfill electronic-warfare demands. This places especially demanding requirements on circulator size and performance. Raytheon recently developed a 6 to 18 GHz circulator under Navy sponsorship to address these applications.(2,3) Performance is summarized in Table II. A key to achieving operation over this bandwidth was introduction of a secondary lower saturation magnetization ferrite to reduce the spatial non-uniformity within the ferrite. Minimization of low-field losses over wide excursions of frequency and temperature required a careful selection of materials and geometry.

Broadband circulators operating at mid-to-high microwave frequencies such as those described above are invariably distributed in nature and the minimum junction size is dictated by the dimensions necessary to support two counter-circulating modes. Lumped element designs can be considerably more compact but they are not useful for wide fractional bandwidths. (4) Also ohmic loss at higher microwave frequencies becomes excessive. Fortunately, a large number of military and commercial applications fall within the range of frequencies (≤ 3 GHz) and fractional bandwidths (≤ 10%) which are most appropriate for lumped element technology. An example of a recently developed Raytheon lumped element circulator (5) is given in Table III. Smaller versions (.1" wide hexagonal disks) have exhibited less than .3 dB insertion loss and a 20 dB isolation bandwidth of greater than 5%.

Table II. Microstrip Circulator - (Raytheon)

Frequency:	6 to 18 GHz
Insertion Loss:	≤ 1.0 dB (≤ .6 dB from 6.5 - 17.5 GHz)
Isolation:	≥ 14 dB (≥ 18 dB from 6.5 - 18 GHz)
VSWR	< 1.2:1
Phase Tracking	± 5°
Amplitude Tracking:	±.1dB
Size:	.140" x .275" x .6"

Table III. Lumped Element Circulator - (Raytheon)

Frequency:	1.15 to 1.40 GHz
Insertion Loss:	0.5 dB
Isolation:	20 dB
Weight:	1.8 grams
Ferrite Size:	.2" (hex) x .02"

Circulator design is currently based on Bosma's (6) work and extensions thereof. This model is idealized in several respects, i.e. non-rigorous boundary conditions, absence of loss and homogeneous media are assumed. The need for improved performance has resulted in some progress in removing these restrictions. Although no rigorous treatment of boundary conditions for microstrip or stripline circulators has been reported, the restrictive "magnetic wall" boundary condition has been removed for stripline ferrite resonators.(7) Dielectric, magnetic and ohmic losses have been recently incorporated into the Bosma formulation.(8) Finally, considerable progress has been made in understanding magnetic field inhomogenuities and their relationship to low-field losses.(9) The high level of current theoretical activity will undoubtedly lead to even more advances in the near future.

Single-Crystal Yttrium-iron-garnet Devices

The low intrinsic magnetic and dielectric losses of yttrium-iron-garnet have led to its wide usage in microwave resonator devices such as filters, tunable-oscillators and limiters. The most common geometry employs YIG-spheres coupled to wire loops. More than twenty years ago growth of high quality epitaxial YIG films was demonstrated on a good microwave substrate, gadolinium-gallium-garnet. Since that time there have been numerous efforts in the US to develop inexpensive planar YIG devices based on either magnetostatic wave delay lines or resonators. After a flurry of activity in the seventies to mid-eighties, interest in this technology diminished because the anticipated economic and technical benefits were not perceived to be sufficient to dislodge well-entrenched existing approaches. One area where YIG-film technology still appears to offer size and performance advantages over competitive approaches is in compact frequency channelizers for signal sorting in electronic warfare receivers.(10) A program to benchmark the technology for this application is currently ongoing at Westinghouse under Navy sponsorship.

Another promising application for YIG film technology is highly compact filters for phased array or communications applications. Performance of a 3-pole notch filter employing 1 millimeter diameter film resonators is given in Table IV.(11) The unit employs a combination of a permanent (Nd-Fe-B) magnet and an electromagnetic to achieve the 1 cm^3 package volume.

Table IV. MSW Notch Filter - (Westinghouse)

Tunable frequency range:	8 to 10 GHz
3 dB Bandwidth:	100 MHz
40 dB Rejection bandwidth:	25 MHz
Size:	1 cm x 1 cm x 1 cm

A unique capability of ferrite technology is that of frequency selective limiting. In contrast to the widely employed PIN limiter which attenuates all signals within a passband in the presence of a large signal, the frequency selective limiter attenuates the high-level signal while leaving low-level signals which are a few tens of MHz removed in frequency unaffected. A low magnetic linewidth is necessary to place the threshold for limiting at useful power levels thus YIG is again the magnetic material of choice. Although the concept of limiting over a broad instantaneous bandwidth in a planar geometry was demonstrated in the early 1980s (12) it is only recently that high performance limiters have been demonstrated.(13) The improved limiter utilizes a stripline configuration to achieve a high filling factor. Performance is summarized in Table V. By cascading multiple strips with amplifiers, signals with input power levels over a 60 dB range were compressed into a range of 6 dB at the output.

Table V. Frequency Selective Limiter - (Westinghouse)

Frequency:	2.5 - 5.3 GHz
Small signal loss:	3 dB
Limiting threshold:	0 dBm
Amount of limiting (+19 dBm):	14 dB

High Power Components

Ferrite phase shifters are commonly employed when high power handling and/or low insertion loss are critical. Common applications are phase-scanned antennas and non-reciprocal phase-shift sections for high power differential phase shift circulators. Radar and electronic warfare systems in the US military rely heavily on vacuum tube sources of microwave power which in turn require ferrite control components for performing functions such as duplexing and phase-shifting.

At lower microwave frequencies rotary-field type phase shifters are commonly used for applications requiring excellent phase accuracy (~1°) as well as high peak and average power, typically tens of kilowatts peak and hundreds of watts average at C-band. Microwave Applications Group has provided many recent innovations to this component (14,15), the latest being a factor of four increase in its average power handling capability. The underlying approach was to segment the circular waveguide section into a series of ferrite disks separated by high thermal conductivity dielectric disks to lower the overall thermal resistance.

The ferrite toroidal-phase shifter is especially useful at the microwave and millimeter wave frequencies where wide bandwidth and/or low loss is important. It is commonly constructed in a latching configuration so that no holding current is required once the unit is switched to the desired state. The ferrite toroid fully fills the waveguide from top to bottom and is commonly put under a slight compression to prevent air gaps at the waveguide-ferrite interface. As the device temperature changes due to changes in ambient or RF heating, differential thermal expansion can create both a top-to-bottom stress and a longitudinal stress. The change in stress results in a change of magnetization, and hence phase shift, via the magnetostrictive effect. Several current US DoD applications demand extremely tight phase control and thus cannot tolerate any appreciable stress sensitivity. A common approach to minimizing this problem has been to use a material with low sensitivity to temperature variations, YIG (13% Gd), with a small amount of Mn^{+3} incorporated into the structure to reduce magnetostriction. Electromagnetic Sciences, under Navy sponsorship, is currently investigating approaches to further minimize magnetostrictive effects. One of the principal results to date is that by increasing the Mn content from .09 Mn per formula unit, the most widely used composition for low magnetostriction at present, to .13 to .15 Mn per formula unit, the magnetostrictively induced phase shift can be reduced up to an order of magnitude.(16)

There has been no completely satisfactory solution to phase shifting for wide fractional bandwidths (50-100%) at I-J bands for two dimensionally scanned phased-array antennas. FET phase shifters are extremely small and consume little prime power but can handle only moderate amounts of RF power and commonly exhibit ~ 10 dB insertion loss. PIN phase shifters exhibit a few dB less loss and greater power handling capability but commonly consume an unacceptably high amount of prime power. Ferrite technology would appear to offer a useful alternative but planar configurations have proven impractical and rectangular waveguide configurations are excessively large and costly. An improved ferrite configuration was recently reported by Electromagnetic Sciences. They used a hybrid microstrip/dual-toroid design to achieve a six to one reduction in volume as compared to conventional designs. The experimental model operated over the 8-10 GHz band with a nominal insertion loss of 1 dB, and a return loss of greater than 17 dB.

<u>Monolithic Circuit Technology</u>

New ferrite initiatives are emphasizing lower cost and reduced size and weight in order to find a niche in the growing monolithic circuit market. Near term cost reductions will occur mainly from improved batch processing techniques, e.g. forming a composite dielectric-ferrite block of material and slicing it to produce individual circuits.(3) A longer term goal is to employ photolithographically defined film geometries with self-bias or magnetic thin film permanent magnet bias.

Several promising ferrite film deposition techniques have already been demonstrated (17-19) and numerous other will be investigated under upcoming ONR and DARPA initiatives. The ONR program will be a five-year basic research effort to study the behavior of magnetic materials in "small" structures. Elements of the program will entail magnetic oxide film growth (including multi-layer structures), understanding novel properties of these structures and optimizing materials for novel device (optical, memory, microwave) implementations. The DARPA program will be investigating numerous compact low cost approaches to microwave circulators and filters.

There are several obstacles to be overcome before a viable monolithic ferrite-film distributed circulator can be produced. Thick ferrite films of good quality must be grown to achieve acceptable circulator loss, isolation and bandwidth, especially for the distributed geometries required for large fractional bandwidths. For example, predicted performance of a 50% bandwidth C-band design deteriorated rapidly when the thickness was reduced below 125 μm.(20) Low junction impedance is particularly troublesome; it can be alleviated with innovative junction (21) or reduced filling factor (22) geometries but only at the expense of reduced bandwidth. Film technology appears to be better suited to miniature lumped element designs. Furthermore, photolithographic patterning of film geometries is highly conducive to low cost production.

The greatest payoff in terms of size and weight reduction of circulators would be elimination of the external biasing magnet and its associated circuitry. Two promising approaches have been suggested for doing this. The first is to incorporate thin-film magnets made from materials such as Sm-Co and Nd-Fe-B directly into the microwave structure.(23) Films with energy products of ~20 kg-Oe have been demonstrated with easy axes of magnetization either in-plane or perpendicular to the plane. Thicknesses up to 100 μm appear feasible which should be adequate for some circulator configurations but to date no concerted effort has yet been made to produce a thin film magnet device.

A second promising approach to elimination of the bias magnet is to utilize one of the class of uniaxial ferrites such as the barium-strontium-ferrites. These ferrites have a high internal field which provides a self-bias for the circulator. A circulator based on this principle exhibited more than 20 dB isolation over a 2 GHz bandwidth at 31 GHz with a midband insertion loss of 1 dB.(24) The limits of this approach have not been explored but in principle it is scalable to higher and lower frequencies as well as wider bandwidths with proper material and geometry design.

CONCLUSIONS

There has been steady progress in advancing the state-of-the-art in ferrite devices in the United States over the past several years despite only modest governmental and industrial investment in this technology. Microstrip circulator technology at microwave frequencies has advanced to the point where cost and manufacturability rather than performance, are the major issues and a large fraction of the US DoD ferrite-device investment over the next several years will be allocated to their resolution. Extensive commercial application is also anticipated. A primary goal is to produce a ferrite device which is compatible in size and cost with monolithic microwave circuits. Technology developments within the past few years now make this feasible for certain applications.

Activity in thin-film YIG filter technology has been waning in the United States over the past few years but the intrinsically high Q of YIG resonators and the compatibility of film technology with monolithic circuits (where high Q resonators are difficult to realize) may reverse this trend. Elimination of the external bias magnet for fixed tuned applications would greatly enhance its utility.

Vacuum electronics will continue to play an important role in future military systems. There is currently a substantial Tri-Service initiative to advance this technology along many fronts - microwave power modules, vacuum microelectronics, millimeter-wave amplifiers, crossed field devices etc. in support of military requirements. The power handling capabilities of control components e.g. duplexers and switches, required to support the advancing vacuum electronic technology will in most cases require a ferrite implementation thus a reasonable investment in high-power ferrite technology will be required to optimize system performance.

In summary, the next few years are expected to see a increased activity in ferrite science and technology and major advances in the state-of-the-art can be anticipated.

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