Integrated Self-Biased Hexaferrite Microstrip Circulators for Millimeter-Wavelength Applications

S. A. Oliver, P. Shi, W. Hu, H. How, S. W. McKnight, N. E. McGruer, P. M. Zavracky, and C. Vittoria

***Abstract*—Planar microstrip Y-junction circulators have been fabricated from metallized 130-μm-thick self-biased strontium hexaferrite ceramic die, and then bonded onto silicon die to yield integrated circulator circuits. The impedance matching networks needed to transform the low-impedance circulator outputs were deployed on low-loss alumina or glass dielectrics to minimize circuit losses. These magnetically self-biased circulators show a normalized isolation and insertion loss of 33 and 2.8 dB, respectively, and a 1% bandwidth for an isolation of 20 dB. Application of small ($H < 1.5$ kOe) magnetic bias fields improved the isolation and insertion loss values to 50 and 1.6 dB, respectively. This design may form the basis for future monolithic millimeter-wave integrated circulator circuits that do not require magnets.**

***Index Terms*—Circulators, ferrite devices, ferrites, microstrip components, millimeter-wave devices, millimeter-wave integrated circuits.**

I. Introduction

The value of integrating planar ferrite components along with semiconductor substrates in microwave integrated circuits may become compelling if good device performance is retained while obtaining significant decreases in the component size and weight [1]–[4]. For example, the application of planar Y-junction circulators at millimeter wavelengths becomes particularly favorable because the diameter of the resonator junction scales with wavelength. This decrease in resonator size can be further enhanced by using self-biased hexagonal ferrites, or hexaferrites, as the gyromagnetic medium since the large dielectric constant ($\varepsilon_r \sim$ 21–23) measured for hexaferrites further reduces the component size compared to that of garnets or spinel ferrites ($\varepsilon_r \sim$ 10–15). Moreover, the large uniaxial anisotropy fields present in hexaferrites can be used to provide ferrimagnetic self-resonant frequencies above 40 GHz in oriented materials when they are self-biased, i.e., behave as permanent magnets. This material property can be used to rid the component of external magnets, greatly reducing the overall circulator size [1], [5]–[8]. Thus, planar microstrip Y-junction circulators fabricated from hexaferrite materials appear to be excellent candidates for incorporation into millimeter-wave integrated circuits.

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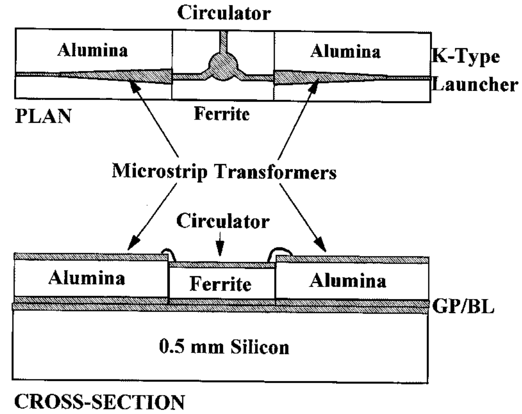

Fig. 1. Plan-view and cross-sectional schematics of the integrated circulator circuit (not to scale). GP/BL indicates the ground plane/bond layer. The plan view does not show the third (upwards) microstrip line.

In this paper, we describe the fabrication and performance of integrated planar microstrip circulator circuits operating at K_A-band. These circulator circuits anticipate the considerations needed to combine hexaferrite films with semiconductor substrates to yield low-loss microwave integrated circuits, including the batch processing of circulators that use minimal hexaferrite material, the integration of ferrites and dielectrics with metallized silicon wafers, and the placement of the impedance matching networks on the dielectrics to reduce the overall system losses. Thus, this paper builds on previous results obtained on both microstrip hexaferrite circulators [6] and integrated ferrite–film/semiconductor microstrip circulators [2], [3].

II. Integrated Circulator Fabrication

The hexaferrite permanent magnet starting materials were oriented strontium hexaferrite ($SrFe_{12}O_{19}$) ceramic pucks that showed good square loop hysteresis behavior with a remanent flux density (B_r) of 4.1 kG and a coercive field value (H_{cJ}) of 2.9 kOe. Sections of these pucks were diced, ground, and polished using standard metallographic techniques to obtain 1.5 cm $\times$ 1 cm $\times$ 130-μm-thick chips, where the internal magnetic field lay normal to the chip surface. These chips were then metallized on both faces with 3 μm of copper sputtered onto a TiW adhesion layer, thus ensuring high conductivity for both the transmission line and ground plane. Batches of Y-junction microstrip circulators were fabricated by patterning the top-face copper using standard photolithographic and wet-etching processes, and then dicing the patterned piece into 3 mm $\times$ 3 mm die for transfer and bonding to the silicon substrates.

The planar ceramic circulators were integrated with silicon substrates by bonding the circulator onto 2.5 cm $\times$ 2.5 cm silicon die that had previously been metallized by a 2.5-μm-thick copper film. Fig. 1 provides a plan view and cross-sectional schematic of the circulator circuit. Permanent bonds were provided using high-conductivity silver epoxies cured at 200 °C. Temporary bonds using silver paint were also used in the testing of several circulator circuits.

Impedance matching microstrip lines were placed on dielectric substrates abutting the hexaferrite die. These matching structures consisted of linear tapered microstrip lines having an electrical length of 2λ that were patterned onto metallized substrates of either 0.005-in low-loss alumina or 0.010-in low-loss fused silica. These substrates were also bonded onto the metallized silicon substrate, as per Fig. 1, with the microstrip-line connections being made by wire bonding. Finally, the circulator circuit was mounted onto a test block, and connections to

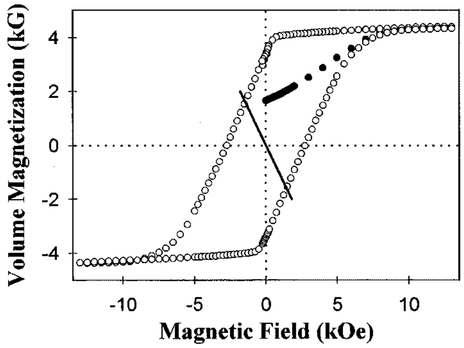

Fig. 2. Magnetization versus applied magnetic-field behavior of a strontium hexaferrite circulator die. Hysteresis loop (∘), initial magnetization (•), magnet load line (solid line).

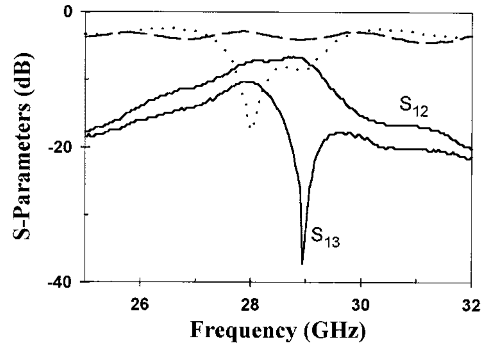

Fig. 3. Scattering parameter (S_{11}, S_{21}, S_{31}) results versus frequency for an as-produced self-biased circulator circuit. The S_{11} data is the dotted line. The dashed line shows transmission results when an impedance-matched microstrip line replaces the hexaferrite chip in the circuit.

the external 50-Ω coaxial lines were made using asymmetrically offset type-K coaxial-line-to-microstrip-line launchers.

The hexaferrite circulator was designed to operate above resonance since the self-resonant ferrimagnetic resonance (FMR) frequency, as provided by the internal field (H_i) as $f = (\gamma/2\pi)H_i = (\gamma/2\pi)(H_A - 4\pi M)$ lies at a much higher frequency than the desired circulator operating frequency of 30 GHz. Here, γ is the gyromagnetic constant ($\gamma/2\pi = 2.8$ GHz/kOe) and H_A is the uniaxial anisotropy field ($H_A = 19.5$ kOe) for strontium–hexaferrite. Values for the resonator junction radius and port suspension angle were obtained by performing an extremum search of the circulator performance over all parameters in the circulator design parameter space. In particular, the values were chosen such that the circulator maintained good isolation and insertion loss over maximal bandwidth while remaining relatively insensitive to the exact values of design parameters such as the internal field and FMR linewidth. This approach allowed for circulator operation under different magnetic biasing conditions, which may vary the internal field by almost 3 kOe, depending on the value of the magnetization as given by the hexaferrite hysteresis loop. This design also incorporated the effects of fringing fields that act to increase the effective resonator junction radius and, thus, lower the operating circulator frequency. The results of this design yielded a junction radius of 0.054 cm, while the total angle sub-tended by the output port was 0.56 rad.

In contrast to typical circulators, no magnetic flux closure structure was incorporated into the integrated circulator circuit. Hysteresis loops were measured on the patterned hexaferrite die to appraise the magnetic properties of the circulators before and after magnetic poling. Fig. 2 shows the volume magnetization ($4\pi M$) versus applied magnetic field (H) behavior of a 130-μm-thick hexaferrite circulator, where the open circles show the major hysteresis loop behavior of this circulator as it is magnetically poled normal to the plane. Here, the major loop is skewed because of the strong demagnetizing fields in this thin plate geometry. The volume saturation magnetization value ($4\pi M_s$) was 4.4 kG. The magnet operating condition was given by the intersection of the magnet load line with the hysteresis loop in Fig. 2 [8], [9]. Here, the load line is found from $4\pi M = -H/N_z$, where N_z is the demagnetizing factor normal to plane of the hexaferrite chip. For this thin plate geometry, the value of N_z is approximately 0.9. The resulting intersection occurs at $4\pi M = 1.6$ kOe, a value that was confirmed by measuring the initial magnetization curve of the circulator weeks after being magnetically poled, as per the solid circles in Fig. 2. This reduction in net magnetization decreases the effective gyrotropy of the hexaferrite and, thus, key circulator parameters such as the bandwidth. It also raises the value of the internal field. These demagnetizing effects may be mitigated by developing hexaferrites having large coercive fields, such that magnetization values approaching the remanence value can be maintained even for very thin hexaferrite die [9].

III. RF Measurements and Discussion

S-parameters for the integrated circulator circuits of Fig. 1 were measured on a Hewlett-Packard HP 8510B vector network analyzer at a power level of 10 dBm. Measurements were taken in the isolator configuration where the third port is terminated in a 50-Ω load. Fig. 3 shows digitized data for the S-parameters S_{11} (reflection or return loss), S_{21} (transmission or insertion loss), and S_{31} (isolation) of an as-produced circulator circuit over the frequency band from 25 to 32 GHz. All circulators showed maximum isolation at frequencies slightly below the designed f_c of 30 GHz. This effect may be due to the hexaferrite having a lower than expected dielectric constant. The circulator circuit of Fig. 3 shows a maximum isolation value of 37 dB at 28.9 GHz, with a corresponding insertion loss of 6.9 dB. From the S_{31} data, it is noted that the minimum in reflection occurs at a lower frequency than that of maximum isolation, indicating a slight mismatch in tuning.

In addition to the circulator circuit S-parameters, Fig. 3 also shows digitized transmission data (dashed line) where the hexaferrite circulator chip was replaced in the circuit by an impedance-matched microstrip line on alumina. This curve approximates the losses incurred in the test mount connectors and launchers, microstrip lines on alumina, and wire bonds. At 28.9 GHz, this curve has an insertion loss of 4.3 dB, indicating that the remainder of the planar microwave circuit, and connectors, are the largest contributors to the overall circulator circuit loss. Upon normalizing the effects of the transmission lines and connectors, the self-biased hexaferrite circulator was found to have an insertion loss of 2.8 dB, and an isolation of 33 dB. The bandwidth of this circulator was 1% for an isolation of 20 dB.

It has been noted from the magnet operating condition shown in Fig. 2 that the hexaferrite chip was partially demagnetized and, thus, does not recover the maximum possible values for magnetic polarization ($4\pi M_s$) or effective permeability [10]. Thus, the circulator circuits were also measured with a permanent magnet biasing the resonator junction. Here, the small magnetic field ($H < 1.5$ kOe) was insufficient to saturate the material, with the circulator magnetization lying on a minor hysteresis loop within the major loop of Fig. 2. All circulators showed improved values for the insertion loss and isolation when tested with the biasing magnet compared to their as-produced results. Fig. 4 shows normalized S-parameter results S_{21} and S_{31} obtained by biasing the circulator of Fig. 3 with the permanent magnet, where the circulator now shows a normalized insertion loss of 1.6 dB and an isolation of 50 dB. No significant increase was observed in the

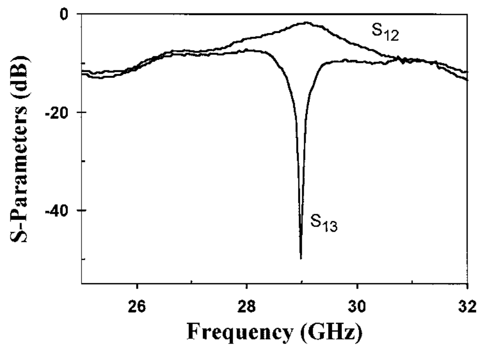

Fig. 4. Normalized scattering parameter (S_{21}, S_{31}) results versus frequency for the same circulator as shown in Fig. 3, with this circulator biased with $H < 1.5$ kOe.

circulator circuit bandwidth, nor did it prove possible to adjust the frequency where maximum isolation occurs to coincide with the minimum in S_{11}. However, these improvements further indicate the importance of the hexaferrite magnetic properties, and the state of magnetization, in determining the circulator performance.

Considerable improvements can be expected in the performance of the circulator circuits presented here by developing hexaferrite materials having large coercive fields and smaller magnetic and dielectric absorption, and by improved tuning and decreased losses in the microstrip matching network. In addition, transmission-line losses might be greatly reduced at the systems level by designing other components to match the low-output impedance of these thin planar circulators. With these refinements, integrated planar hexaferrite circulators may become as prevalent as ferrite waveguide components.

References

[1] E. F. Schloemann, "Circulators for microwave and millimeter-wave integrated circuits," *Proc. IEEE*, vol. 76, pp. 188–200, Feb. 1988.

[2] J. D. Adam, H. Buhay, M. R. Daniel, M. C. Driver, G. W. Eldridge, M. H. Hanes, and R. L. Messham, "Monolithic integration of an X-band circulator with GaAs MMIC's," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1995, pp. 97–99.

[3] S. A. Oliver, P. M. Zavracky, N. E. McGruer, and R. Schmidt, "A monolithic single-crystal yttrium iron garnet/silicon X-band circulator," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 239–241, Aug. 1997.

[4] H. How, S. A. Oliver, S. W. McKnight, P. M. Zavracky, N. E. McGruer, C. Vittoria, and R. Schmidt, "Theory and experiment of thin-film junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1645–1653, Nov. 1998.

[5] N. Zeina, H. How, C. Vittoria, and R. West, "Self-biasing circulators operating at Ka-band utilizing M-type hexagonal ferrites," *IEEE Trans. Magn.*, vol. 28, pp. 3219–3221, Sept. 1992.

[6] J. A. Weiss, N. G. Watson, and G. F. Dionne, "New uniaxial-ferrite millimeter-wave junction circulators," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, 1989, pp. 145–148.

[7] Y. Akaiwa and T. Okazaki, "An application of a hexagonal ferrite to a millimeter-wave Y circulator," *IEEE Trans. Magn.*, vol. MAG-10, pp. 374–378, June 1974.

[8] M. A. Tsankov and L. G. Milenova, "Design of self-biased hexaferrite waveguide circulators," *J. Appl. Phys.*, vol. 73, pp. 7018–7020, May 1993.

[9] P. Campbell, *Permanent Magnet Materials and Their Application*. Cambridge, U.K.: Cambridge Univ. Press, 1994.

[10] J. J. Green and F. Sandy, "Microwave characterization of partially magnetized ferrites," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 641–645, June 1974.

Accurate RF Large-Signal Model of LDMOSFETs Including Self-Heating Effect

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***Abstract*—In this paper, we present a new silicon RF LDMOSFET large-signal model including a self-heating effect. A new empirical channel current model suited for accurately predicting intermodulation distortion is employed. The proposed channel current model can represent transconductance (gm) saturation and rolloff in the continuous manner. It has continuous higher order derivatives for accurate prediction of nonlinear microwave circuit behavior, such as power amplifiers, microwave mixers, oscillators, etc. Using the complete large-signal model, we have designed and implemented a 1.2-GHz power amplifier. The measured and simulated amplifier characteristics, especially the intermodulation and harmonic behaviors, are in good agreement.**

***Index Terms*—Empirical channel current model, large-signal model, LDMOS, self-heating effect.**

I. Introduction

The recent advances of the silicon RF LDMOSFET technology make it possible to use the device for over 2-GHz band [1]. Due to the high gain and good linearity, LDMOSFET offers a good alternative to GaAs MESFET and silicon bipolar junction transistor (BJT) for L- or S-band power amplifiers [1]. For the circuit design using a nonlinear circuit simulator, an accurate large-signal model in the RF band is required. Previous physical models, such as the BSIM3V3, have too many parameters and too complex extraction routines [2], [3]. The table-based models have problems with a relatively long simulation time, no capability to include self-heating effects, and less accuracy to predict distortion behavior of power amplifiers [2]–[4]. Miller *et al.* [5] introduced an empirical large-signal model of RF LDMOSFET. However, Miller's model could not express the channel current saturation for a large gate-bias voltage. This may cause an inaccurate rolloff of transconductance. Here, we propose a compact channel current model with improved characteristics. It employs fewer parameters, but accurately describes transconductance rolloff to near zero and self-heating effect.

For power amplifiers, self-heating could lead to the premature breakdown of the device, and could degrade the power performance to a considerable extent with a large rise in channel temperature [6], [7]. In LDMOSFET, like conventional MOS transistors, the self-heating degrades the effective mobility and linearly reduces the threshold voltage (V_T). Thus, the temperature rise increases the drain current due to the reduced threshold voltage at a low-current region and decreases it due to the effective mobility degradation at a high-current region [8], [9]. Hence, a large-signal model must describe the self-heating effect properly.

In this paper, we present an accurate LDMOSFET large-signal model including a dynamic self-heating effect. A new channel current model equation has a continuous expression of transconductance (gm) and its higher order derivatives ($gm2$, $gm3$, ...) to accurately predict intermodulation distortion characteristics of the nonlinear microwave circuits. It includes thermal circuit of a low-pass structure to account

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