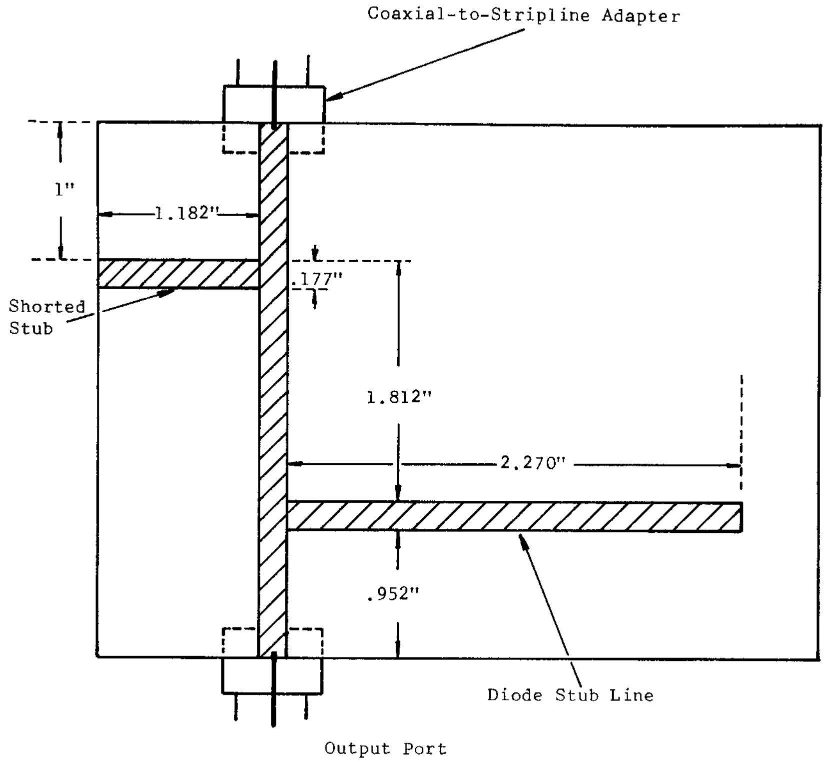

Fig. 1. Center conductor layout for the switch.

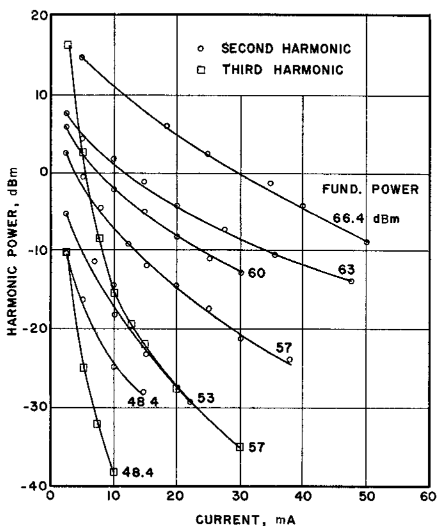

Fig. 2. Generated harmonic powers for forward bias.

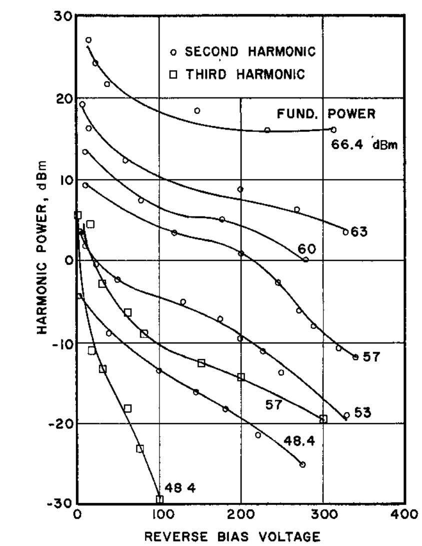

Fig. 3. Generated harmonic powers for reverse bias.

by the diode, but for the third harmonic the diode-generated values exceed those shown by 3.5 dB, as discussed previously.

One of the more noteworthy features of these curves is the relatively high harmonics produced at low bias levels, for both forward and reverse bias. It is also apparent that for either bias state the harmonics increase with an increase in incident power at a faster rate than that of the incident power level. This agrees with the findings of Hunton and Ryals for a 12-diode stripline attenuator.[3]

[3] J. K. Hunton and A. G. Ryals, "Microwave variable attenuators and modulators using PIN diodes," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 262–273, July 1962.

An increase in harmonic level with decrease in forward-bias current is to be expected, and this is apparent in Fig. 2. For very low bias currents insufficient charge is stored in the intrinsic region of the diode and this is depleted during the negative half cycle of the RF current, giving rise to a nonlinearity with high harmonics. With the assumption of a minority carrier lifetime of 0.2 μs the point of charge depletion is determined to be about 10 mA for an incident power of 2.5 kW peak. Although there is no discontinuous increase in harmonics appearing near this bias in Fig. 2, it may be seen that the harmonic content is changing rapidly at that point.

One may also observe in Fig. 3 for reverse bias that harmonics are high for low bias voltages. In this range charge is injected into the intrinsic region on positive swings of the signal and nonlinearities are caused by recombination. With increasing bias voltages the harmonics are seen to decrease. At a bias voltage equal to the zero-peak RF voltage on the diode, charge injection no longer takes place. This point occurs for the second-harmonic curves marked 48.4 and 53 dBm of Fig. 3 at 84 and 141 volts bias, respectively.

As reverse-bias voltage increases the negative peaks of the RF signal drive the diode beyond its reverse bias (dc) breakdown value. This point occurs on the 66.4 dBm curve of Fig. 3 at a bias of 105 volts (with a breakdown voltage for this diode of 760 volts). One might expect an increase of harmonic content for a further increase of bias voltage. While the curves of Fig. 3 could not be extended sufficiently to ascertain this increase definitely it appears that the 66.4 dBm curve has leveled out and perhaps has started to rise for larger bias voltages.

Finally, we wish to note that no harmonics higher than the third were observed with the spectrum analyzer which had a sensitivity of about −60 dBm for the pulsed signal used.

ACKNOWLEDGMENT

The authors wish to express their appreciation to J. W. Harper and D. Stone of the Marshall Space Flight Center for their valuable assistance.

HAROLD MOTT
DAVID N. MCQUIDDY
University of Alabama
University, Ala.

Phase Shifter in C-, X-, and Ku-Bands Using Segregated-Mode Resonance in Single Crystal YIG

Single crystal YIG has long been regarded as an ideal material for ferromagnetic resonance type devices. However, the performance of all such devices is far from ideal due to excitation of spin-waves at moderate power levels. The excitation of these spurious responses limits the device's power handling capability, as well as degrades its performance, such as insertion loss, noise figure, etc. In order to extend the usefulness of this material, it is necessary, either to suppress all spin-waves, or to segregate one resonant mode out of the manifold.

Single mode segregation has been achieved in a thin YIG disk coupled to a rutile resonator and in a YIG sphere of radius larger than the excitation wavelength (all the YIG samples being single crystal). We have reported and discussed our experimental data relating to such effects elsewhere.[1] Here, we

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[1] K. K. Chow and M. E. Hines, "Mode segregation effects in single-crystal YIG," *J. Appl. Phys.*, vol. 37, pp. 5000, December 1966.

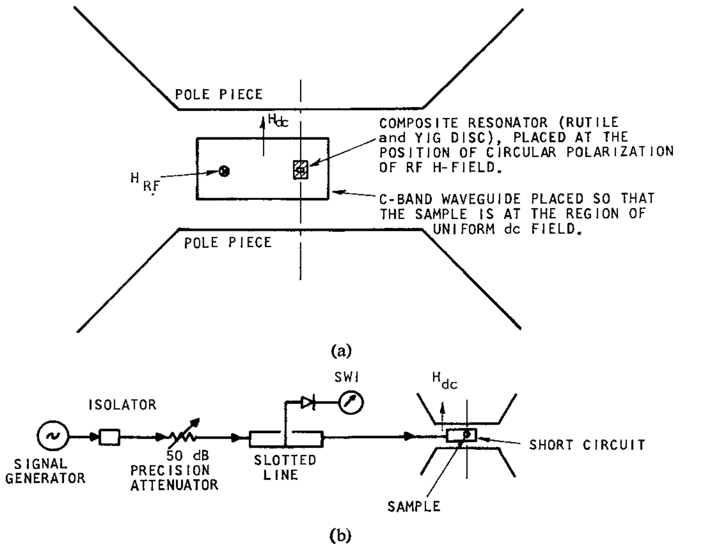

Fig. 1. Experimental setup for the measurement of phase-shifting characteristics; (a) the sample and its position relative to dc and RF H-fields, and (b) microwave circuit.

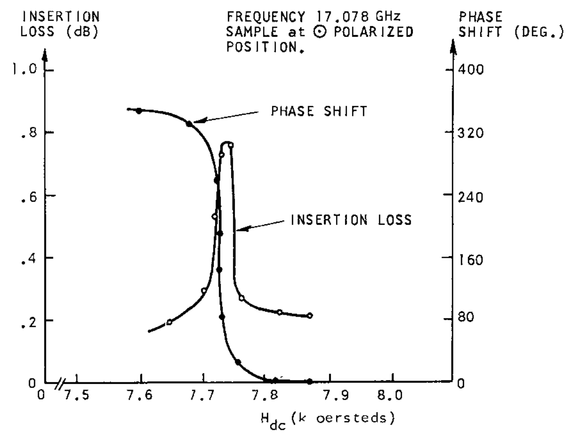

Fig. 2. Phase shift and insertion loss characteristics of the segregated mode of a large sphere at Ku-band.

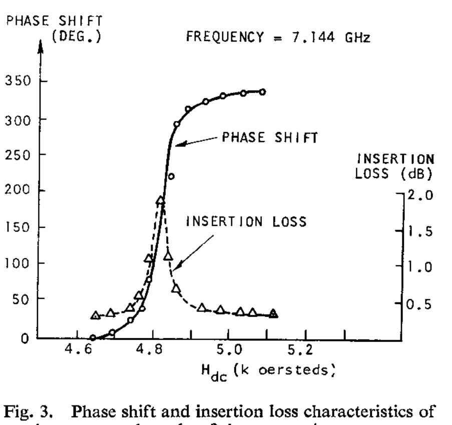

Fig. 3. Phase shift and insertion loss characteristics of the segregated mode of the composite resonator at C-band.

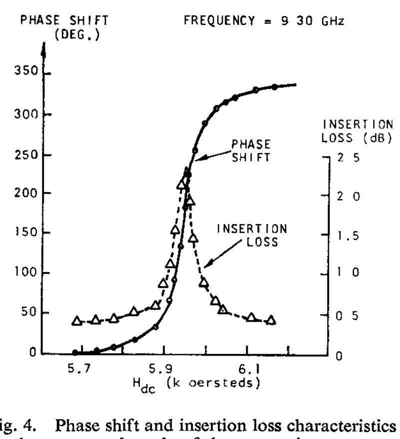

Fig. 4. Phase shift and insertion loss characteristics of the segregated mode of the composite resonator at X-band.

wish to report the results of using the segregated mode in phase shifters in the frequency band 4–18 GHz.

The sample (either the composite resonator or the large sphere) is placed in a rectangular waveguide at the position of circularly polarized RF H-field and the entire assembly is placed in the region of uniform dc H-field (5 parts in 10^4 uniformity in a volume >0.500 inch cube), as shown in Fig. 1(a). It should be noted that this uniformity is not essential, since the performance is substantially unchanged upon perturbing the field by inserting magnetic material near the pole pieces. For the disk, the plane is perpendicular to the (1 0 0) axis which is parallel to H_{dc}, while for the sphere, the (1 1 0) axis is perpendicular to H_{dc}. The H_{RF} field is perpendicular to H_{dc} in all cases. Microwave circuits employed for these measurements are shown in Fig. 1(b), with the excitation frequency and dc H-field adjusted for mode segregation. The VSWR and the position of minimum are recorded as H_{dc} is slowly swept through resonance. As H_{dc} is swept through resonance, the position of minimum moved through one-half guide wavelength, corresponding to a total phase-shift of 2π. Insertion loss through the resonance is calculated from the VSWR measurements. Experimental results are given in Figs. 2–4.

Figure 2 gives the results employing the sphere (dia $=0.098$ inch) in Ku-band waveguide. It is seen that a phase shift of 2π is obtained with dc field sweep of over 200 Oe at a bias field of about 7.72 K-Oe. The insertion loss of this crude form of phase shifter is less than 0.8 dB at power level of 5 mW.

A set of special higher-power measurements were carried out to determine the threshold for nonlinear effects. In a test at 15.5 GHz using a reflex klystron as a power source, insertion loss measurements of the phase shifter was measured to be 0.8 dB maximum. No changes in loss were observed when the power was varied between 5 mW to 150 mW.

A second test was made using a pulsed magnetron at 15.5 GHz with 0.01 duty cycle. Accurate insertion loss measurements were difficult because of frequency variations during each pulse. The loss in this setup was constant at 1.75 dB. This higher value is believed to arise because of the nature of our pulsed source and our measurement technique rather than in the higher power levels involved. This same loss value was observed at 10 watts peak and at 30 watts peak. Heating effects were observed, causing a drift in the resonance with time. A test at 50 watts peak was attempted, but heating effects were too rapid for a meaningful loss measurement. However, phase-shift behavior and mode segregation effects were apparently the same at 50 watts as at low level.

Figure 3 gives the results when the composite resonator is employed for phase shifting in the C-band. Again, phase-shift of 2π is observed, the dc field sweep being over 300 Oe at a bias field of 4.81 K-Oe. The insertion loss is high for this particular configuration, being about 2 dB. This high loss is attributed to the poor quality of the YIG disk, as well as the simple design of the resonator and the microwave circuit. Similar results are obtained for operation in the X-band, as seen in Fig. 4.

In conclusion, we have seen that phase

shifters using a segregated mode of single crystal YIG give most encouraging performance even in its crudest form. Performance can, no doubt, be improved with the proper design of microwave circuit, and, in the case of the composite resonator, that of the resonator. It should be pointed out that the segregated mode possesses great potentials in device applications such as filters, paramps, directional couplers, isolators, etc., particularly in the high power realm. The reasons are:

1) Previously, the threshold power for the excitation of spurious responses dictates the useful power level of the device. Now mode segregation from the manifold eliminates excitation of these undesirable responses, as evidenced by our high power tests. Therefore, power level can be greatly increased.
2) Sample size employed for the present single crystal YIG devices has been limited to a minimum because it has been observed that larger sizes give more spurious responses (Walker modes). With the mode-segregation effects, this problem is eliminated and much higher power capacity is now possible since the Q of the material is high.

MARION E. HINES
KUNGTA K. CHOW[2]
Microwave Associates, Inc.
Burlington, Mass

[2] Present address is Lockheed Palo Alto Research Laboratory, Palo Alto, Calif.

Comments on "A Large Signal Analysis Leading to Intermodulation Distortion Prediction in Abrupt Junction Varactor Upconverters"

In the above paper by Perlow and Perlman,[1] the authors use steps that are not mathematically correct and which lead to incorrect results. The authors write the matrix equations for the three-frequency upconverter [(1) and (2)] relating the Fourier coefficients i_1, i_2, and i_3 to the Fourier coefficients of the pump and signal voltages. They then derive an expression for the gain G_i as a function of i_1 the Fourier coefficient of the signal current [(10)]. After expanding G_i in a power series [(12)] they substitute a time function [(13)] for the Fourier coefficient i_1 which is clearly not permissible. They further substitute for i_1 the sum of two sinusoids although (1) and (2) are valid for only a single sinusoid at the input.

That the results are incorrect can be seen as follows. If one drives, but not overdrives, an abrupt junction varactor with frequencies f_{s1}, f_{s2}, and f_p, where f_{s1} and f_{s2} are two input signals whose frequency separation is small and hence fall in the input bandwidth, voltages are generated across the diode at $f_p \pm f_{s1}$, $f_p \pm f_{s2}$, $f_{s1} \pm f_{s2}$, $2f_{s1}$, $2f_{s2}$, and $2f_p$. If the diode sees an open circuit at all frequencies except f_p and narrow bands of frequencies about the input and output frequencies then the only currents that flow due to these voltages are $f_p + f_{s1}$ and $f_p + f_{s2}$. These currents in turn mix with f_{s1}, f_{s2}, f_p as well as doubling to produce voltages at $2(f_p+f_{s1})$, $2(f_p+f_{s2})$, $2f_p+f_{s2}+f_{s1}$, $f_p+f_{s2}\pm f_{s1}$, f_p+2f_{s2}, $2f_p+f_{s2}$, $f_p+f_{s1}\pm f_{s2}$, f_p+2f_{s1}, $2f_p+f_{s1}$. If, as assumed above, the varactor sees an open circuit at all of these frequencies, currents do not flow at these frequencies and no intermodulation is produced even though the gain of the upconverter is a function of drive level. If on the other hand, for example, the impedance seen by the varactor at $f_{s1}-f_{s2}$ is small, current will flow at this frequency which will then mix with f_{s1} to produce a voltage at $2f_{s1}-f_{s2}$ which lies in the input bandwidth. The current at this frequency can then mix with f_p to produce an intermodulation product at $f_p+2f_{s1}-f_{s2}$ which will appear in the output. We thus see that the level of intermodulation is a function of the "out-of-band" impedances and cannot be determined without a knowledge of them. The results derived by Perlow and Perlman are independent of these impedances and hence cannot be correct.

It is interesting to note that if frequencies $f_p+k(f_{s2}-f_{s1})$ can flow in the pump circuit for all k less than n then intermodulation products $f_p+f_{s1}+k(f_{s1}-f_{s2})$ and $f_p-f_{s1}+k(f_{s1}-f_{s2})$ will appear in the output for all k less than n. These currents flowing in the pump circuit as well as currents at $m(f_{s1}-f_{s2})$ flowing in the bias circuit are probably the major cause of intermodulation products in the output. If one overdrives the varactor, however, or uses a graded junction, then higher-order intermodulation products can be generated even in the absence of idlers.

A. I. GRAYZEL
NASA Electronics Research Center
Cambridge, Mass.

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[1] S. M. Perlow and B. S. Perlman, *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp 820–827, November 1965.

S. M. Perlow and B. S. Perlman[2]

Grayzel's conclusion that the mathematics of the paper are not correct seems to be based upon a misinterpretation of the meaning of (10).[1] Equation (10) represents the dynamic transfer characteristic of the upconverter, where i_1 and i_3 represent the instantaneous values of the input and output currents. This transfer characteristic is nonlinear. As the input current is continually increased, the output current finally reaches a certain level which cannot be exceeded. A sinusoidal input current of sufficient amplitude will therefore drive the upconverter into the nonlinear gain region, thereby producing an output rich in spurious content. This transfer characteristic was treated as any other nonlinear transfer characteristic would be analyzed. That is, it was expanded into a Taylor series with sinusoidal inputs. For example, the ΔC vs. V characteristic is not derived using sinusoidal voltage, but when it is analyzed for spurious content, sinusoids are used.

This method of utilizing the upconverter characteristic rather than the diode characteristic was undertaken because of anomalous results for abrupt junction varactors. Using the abrupt junction diode characteristic to predict intermodulation distortion results in an erroneous conclusion. That is, there is no intermodulation distortion. This result is obtained for any square-law diode. However, when these square-law diodes are placed in upconverters or mixers, intermodulation distortion occurs and is due to the nonlinear transfer of the complete device rather than the diode itself. Therefore, an analysis of the complete device's transfer characteristic must be performed to obtain the amplitudes of the intermodulation distortion products.

Grayzel's second criticism is that the level of the intermodulation is a function of the "out-of-band" impedances and cannot be determined without a knowledge of them. He also makes the assumption that the diode sees an open circuit at all frequencies except f_p and narrow bands of frequencies about the input and output frequencies. He says, using this assumption, that no intermodulation is produced even though the gain of the upconverter is a function of drive level.

These assumptions were never made by us. In fact, compensation for any reduced bandwidth is shown in (39) of the paper.

The only assumption made was that the signal, pump, and output circuits were tuned to their resonant frequencies. No mention of circuit G and bandwidth was made. In the intermodulation analysis, only the terms in the expansion that contributed to the intermodulation distortion were used. This implicitly assumes that f_{s1}, f_{s2}, $2f_{s1}$, $2f_{s2}$, $3f_{s1}$, $3f_{s2}$, $2f_{s1}-f_{s2}$, $3f_{s1}-2f_{s2}$, $4f_{s1}-3f_{s2}$, etc., flowed in the signal circuit at full amplitudes. Similarly, $f_p \pm f_s$, $f_p \pm f_{s2}$, $f_p \pm 2f_{s1}-f_{s2}$, $f_p \pm 3f_{s1}-2f_{s2}$, etc., flowed in the output circuit at their full amplitudes also.

Grayzel makes objections to the analysis on several points and on each point he states that our conclusions are incorrect. However, this is not a purely theoretical result that cannot be experimentally verified. Indeed, the experimental results for the parametric upconverter bear these results out. In fact, (36) of the paper[1] has not only been experimentally verified for a parametric upconverter but also for the resistive mixer and even for maser amplifiers. It should be pointed out that these experimental results not only come from our own laboratories but also from measurements made by other companies.

S. M. PERLOW
B. S. PERLMAN
RCA Advanced Commun. Lab.
New York, N. Y. 10013

[2] Manuscript received May 16, 1966.

A. I. Grayzel[3]

There are mathematical inconsistencies in Perlow and Perlman's paper.[1] First, (10) is derived from the relationships of (1) and (2). Equations (1) and (2) are valid for a three-frequency upconverter, i.e., only currents at ω_1, ω_2, and ω_3 flow through the diode. The authors then introduce additional frequencies into (10) and, in fact, claim in their rebuttal that all idler frequencies flow at "full amplitude." Secondly, (1) and (2) are matrix equations relating the Fourier coefficients of the voltages to the Fourier coefficients of the currents. i_1, i_2, and i_3 are defined by the relationships preceding (1) and are not functions

[3] Manuscript received June 8, 1966.