A High Power Phase Shifter for Phased-Array Systems

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Abstract—The design of a small, lightweight, high peak and average power phase shifter is discussed. To achieve the high peak power handling, a small crystal grain technique was employed that resulted in a 14 to 1 power handling improvement. To achieve the high average power handling, a temperature compensated garnet was used along with a novel direct dielectric liquid cooling technique. The structure used to implement the cooling causes dielectric loading of the garnet material which enhances the microwave performance of the device. The results have provided a device capable of 360° of continuous reciprocal phase shift while operating at signal levels of 115-kW peak, and 600-watts average power.

Introduction

IN MANY LARGE phased array systems it is desirable to provide RF phase shifting at the input to rows, columns, or subarrays of antenna element phase shifters. Using this technique, the complexity of the phase control system can be drastically reduced. The phase shifting may be provided by a high power phase shifter; however, the unit must necessarily handle all the power that is distributed to the row, column, or subarray. To provide this high power phase shifting capability, a 115-kW peak 600-watt average power *C*-band phase shifter has been developed. The unit is a Reggia-Spencer [1] type of phase shifter capable of 360° of continuous reciprocal phase shift. It is 2.4 by 2.1 by 8.2 inches in size and weighs less than 1.5 pounds. This paper covers the design and development of the unit.

Ferrimagnetic Material

To begin the design of the unit, the ferrimagnetic material had to be selected. The selection was based on three factors: 1) the saturation magnetization had to be compatible with the frequency of operation and the geometry of the device, 2) the material had to be capable of handling high peak power without limiting, and 3) the material had to be relatively insensitive to temperature to handle the high power.

The value of saturation magnetization was determined by considering the equations for both differential phase shift and ferrimagnetic resonance.

The expression for differential phase shift for a Reggia-Spencer phase shifter is given as [2][1]

$$\Delta\beta = 1.96\beta_d\left(\frac{4\pi M}{f_0}\right)^2 \qquad (1)$$

where

β_d = the phase constant for a dielectric loaded waveguide with the loading being accomplished by the dielectric constant of the ferrimagnetic material

$4\pi M$ = the magnetization of the ferrimagnetic material

f_0 = the center frequency of the operating band.

As may be seen from this equation, the maximum phase shift will occur when the value of magnetization ($4\pi M$) reaches saturation ($4\pi M_s$). If this value is too low, the amount of phase shift per unit length will be low and additional length will be required. This is undesirable since additional length causes increased loss. With this problem in mind, a lower limit of 1000 gauss was selected for the saturation magnetization.

The upper limit was selected from Kittel's equation for ferrimagnetic resonance, given as [3]

$$\omega_0 = \gamma\{[H_0 + H_a + H_{ex} + (N_x - N_z)4\pi M_s] \cdot [H_0 + H_a + H_{ex} + (N_y - N_z)4\pi M_s]\}^{1/2} \qquad (2)$$

where

γ = the gyromagnetic ratio = 2.8 mc/Oe

H_0 = the applied magnetic field

H_a = the anisotropy field

H_{ex} = the exchange field

N_x, N_y, N_z = the demagnetizing factors along the x, y, and z axes, respectively.

For this particular device, the geometry of the ferrimagnetic material may be considered as a long thin rod. The applied field is in the z direction which is parallel to the long axis of the bar. The demagnetizing factors for this case are $N_z=0$, and $N_x=N_y=1/2$. The worst case for resonance is at saturation magnetization where the applied field is approximately 50 oersteds. The value of the exchange field and the anisotropy field was given an approximate value of 25 oersteds each. To keep far removed from resonance, it has been found that a good "rule of thumb" is to set the resonant frequency at half the operating frequency. For operation at C band, ω_0 should then be less than 2800 mc. Using the above values, the maximum saturation magnetization should be limited to about 1800 gauss. Hence, the limits of

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[1] This equation is a simple extension of the perturbation equation developed by K. J. Button and B. Lax.

saturation magnetization of the material were set between 1000 to 1800 gauss.

To achieve the high peak power requirements, a special material was required that could increase the level where the onset of ferrimagnetic limiting begins. Ferrimagnetic limiting is caused by a phenomenon known as spin-wave propagation [4]. The spin waves exist within the ferrimagnetic medium, with the spin dipoles being the mechanism for sustaining wave motion. Normally the spin waves are quite small; however, at a critical power level, known as the threshold limiting point, the waves grow abnormally large. At this point, large amounts of RF energy are transferred to the crystal lattice and are dissipated as heat.

To increase the threshold limiting point, two different mechanisms have been shown to be successful. The first mechanism uses rare earth doping [5] which tends to relax the spin waves rapidly to the lattice and prevents the buildup of abnormally large waves. In this situation, the uniform RF mode can become quite large before the spin waves have a chance to become sufficiently excited to cause limiting. Doping with elements such as samarium, dysprosium, and holmium has been used successfully for this purpose. The second mechanism uses a method which tends to limit the spectrum of spin wave frequencies [6]. This is done by using grain boundaries which cause a sufficient discontinuity to break up the spin waves. As the grain boundaries are reduced, the spin-wave spectrum is in turn reduced, and the threshold limiting point increases. Using this technique, improvements of peak power handling of better than 10 to 1 have been reported by reducing the crystal grain size from 14 to 2 microns [7].

Both rare earth-doped and small grain size materials were investigated, with the latter being selected for the eventual model. The selection was based on peak power handling and insertion loss. In general, it was found that rare earth doping seemed to increase the insertion loss slightly, while making the material small grained did not. The improvement in peak power handling as the crystal grain size was reduced is shown in Fig. 1. As may be seen from the figure, the normal 10–12 micron material limited at about 8 kW while the 5 micron material limited at about 30 kW. When the grain size was reduced to 2 microns, absolutely no limiting was detected up to 115 kW.

Under the influence of heat, thermal energy is imparted to the material which tends to destroy the uniform alignment of spin dipoles. The result is a gradual lowering of saturation magnetization vs. temperature. This, of course, is undesirable, as it results in a temperature-sensitive device. To make the material relatively insensitive to temperature variations, a gadolinium doped yttrium-iron-garnet was used. The gadolinium doping was such that the material had only a 10 per cent variation in saturation magnetization over the temperature range of −80 to +125°C. As will be seen, this temperature stability resulted in an extremely temperature-stable phase shifter.

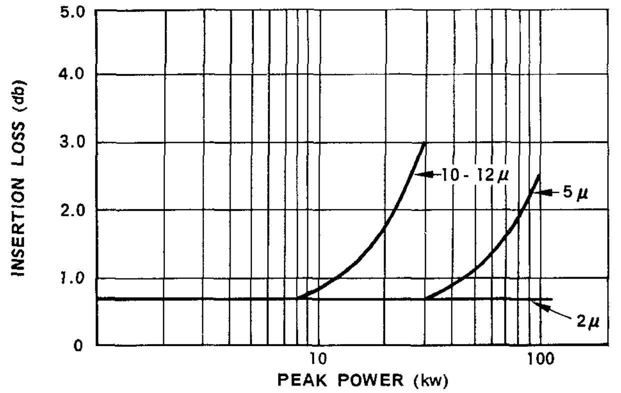

Fig. 1. Improvement of peak power handling vs. crystal grain size.

The final material used was a gadolinium doped yttrium-iron-garnet with a grain size of 2 microns and a saturation magnetization value of 1250 gauss. The material TTG-1001 (small grain) was developed and produced by Trans-Tech, Inc., of Gaithersburg, Md.

Design of the RF Structure

Once the material was selected, the design of the RF structure could begin. The design involved selecting the cross-sectional dimensions of the garnet bar and maximizing the amount of phase shift from this particular bar. The cross-sectional dimensions were obtained from two considerations: 1) the bar should be large enough to support a TE_{11} mode [8], and 2) the bar should not be large enough to support higher order modes [9]. Taking these two considerations into account, and after some experimental work, a bar size of 0.394 by 0.510 inch was selected to operate in WR 187 waveguide.

Maximizing the amount of phase shift can be controlled by three techniques: 1) shaping the input and output transitions of the garnet material, 2) allowing a dielectric gap to exist between the garnet bar and the broadwalls of the waveguide, and 3) side loading the garnet bar with a dielectric.

The shape of the input-output transitions appeared to be the most critical factor in obtaining good phase shift. Various types of transitions were tested, including dielectric quarter wave, dielectric multiple step, garnet wedge tapers parallel to the E plane, garnet wedge taers parallel to H plane, garnet multiple step parallel to the E plane, garnet multiple step parallel to the H plane, and garnet pyramid-shaped tapers. With all of the transitions tested, it was possible to match the unit with a VSWR of less than 1.3 over at least 4 per cent bandwidth. Good phase shift, however, was only obtained with the pyramid shaped tapers. In fact, this matching structure gave better than twice the amount of phase shift obtained with any of the other structures. This re-

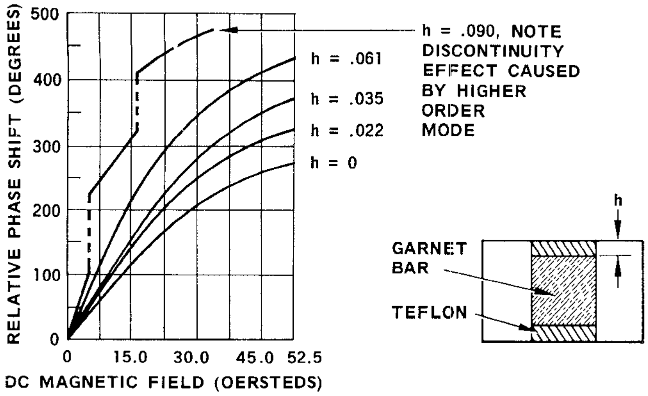

Fig. 2. Improvement of phase shift vs. teflon gap height "h" between garnet bar and waveguide broadwalls.

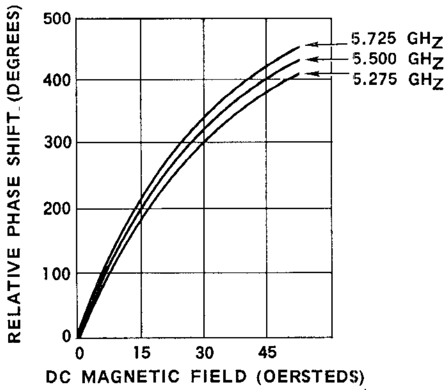

Fig. 3. Relative phase shift vs. magnetic field for three frequencies.

sult seems to agree with Rizzi and Gatlin's conjecture that a TE_{11} mode propagates in the region of the garnet medium.

Additional phase shift can be obtained by allowing a dielectric gap between the garnet bar and the waveguide broadwalls [10], [11]. The height of the gap was obtained experimentally by keeping the garnet-bar height constant and increasing the waveguide height. The waveguide height was varied from direct contact with the garnet bar to a point where multiple reflections began to occur. It is believed that at this point a higher-order mode is propagating in the garnet region that is not matched to the waveguide by the transformers that match the TE_{11} mode. The results of this test for teflon filling are shown in Fig. 2. From the figure, it can be seen that an increase in phase shift of 60 percent, for a given length of garnet bar, was accomplished using this technique.

The final method of improving the phase shift was accomplished by side loading the garnet bar. Here again, teflon was used with an improvement of about 5 percent being obtained. Although this method did not significantly improve the phase shift, it will be seen that it was necessary for implementing the cooling technique.

Using these three techniques, a maximum phase shift of 450° for an effective bar length of four inches was obtained. Curves of phase shift vs. dc magnetic field levels for three frequencies are shown in Fig. 3. The value of 45 oersteds corresponds to 1.0 ampere of drive current. The driving coil utilized two layers of number 24 Form var coated wire. As may be seen from Fig. 3, the bandwidth of the device was 8 percent centered around 5.5 GHz.

Cooling Techniques

Under the operation of high average RF power levels, heat is generated within the garnet bar due to the dissipation of RF energy. As previously mentioned, the heating causes a reduction in the amount of phase shift that can be obtained from a given section of ferrimagnetic material. Thus, to insure stable operation of the phase shifter at high RF power levels, the heat must be removed. To perform this task, a number of cooling techniques were evaluated. Most of the techniques involved the use of a cold plate in the waveguide broadwalls with either the garnet bar being in direct contact with the cold plates or in contact through a thermal conducting dielectric. The direct contact scheme was unsatisfactory because it could not include the technique of phase shift improvement shown in Fig. 2. The indirect contact scheme, through a thermal conducting dielectric, was unsatisfactory due to the large temperature drops incurred across a number of epoxy bond lines.

One cooling technique that was particularly outstanding and could include the phase shift improvements previously mentioned, involved the use of direct dielectric liquid cooling. In this method, shown in Fig. 4, the garnet bar is completely encapsulated in a teflon jacket and a low-loss dielectric liquid is allowed to flow along the surface of the garnet material. By controlling the inlet temperature and the flow of the liquid, the dissipated heat can be directly removed. The success of this method is due to two factors: 1) two-dimensional cooling can be utilized, rather than one-dimensional to a cold plate, and 2) the cooling liquid is in direct contact with the garnet bar, eliminating the large temperature drops incurred across epoxy bond lines. A number of liquids were evaluated, with two meeting the requirements of being both inert and causing negligible insertion-loss increase. These two liquids were 1) FX-78, produced by Minnesota Mining and Manufacturing Company, and 2) perfluorodimethylecyclobutane, produced by E. I. du Pont de Nemours and Company. Both of these liquids caused an insertion loss increase of approximately 0.05 dB. This increase caused the total insertion loss of the device to be 0.90 dB.

Using this cooling technique, a number of tests were made to determine the efficiency of the device. Perhaps the most significant test was the measurement of phase shift vs. dc magnetic fields at various power levels from 0 to 600 watts. In this test, the inlet temperature of the

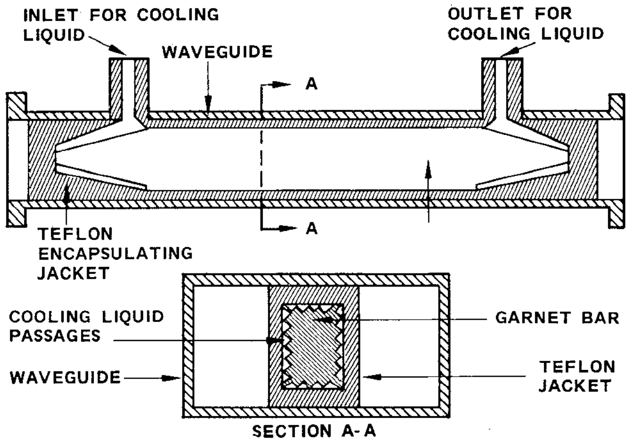

Fig. 4. Direct dielectric liquid cooling technique.

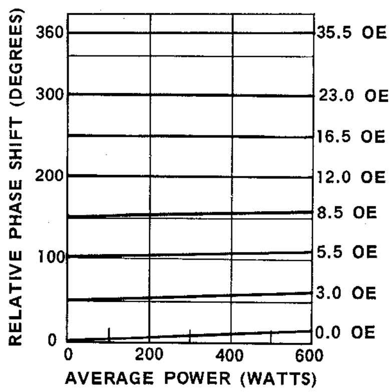

Fig. 5. Phase shift for constant magnetic field levels under average power variations.

cooling liquid was controlled at $72 \pm 10°F$ while the flow rate was controlled at 0.25 ± 0.05 gal/min. The results of this test are shown in Fig. 5. From the figure, it can be seen that the worst power sensitivity occurred at the zero dc magnetic field where the unit had a maximum phase error of 0.012 degrees phase per watt.

Conclusion

Some of the highlights of the design of a small, lightweight, high peak, and average power C-band phase shifter have been covered here. The high peak power handling was achieved by using a special small-grain garnet material, while the high average power handling was achieved by using a temperature compensated garnet along with a rather unique direct dielectric liquid cooling scheme. Because of the unit's small size and weight, the device should be extremely useful for many phased array systems.

A photograph of the device is shown in Fig. 6. The photograph shows the inlet and outlet tubes used to provide the dielectric liquid cooling. Also shown is the connector that provides the driving current that produces the phase shift.

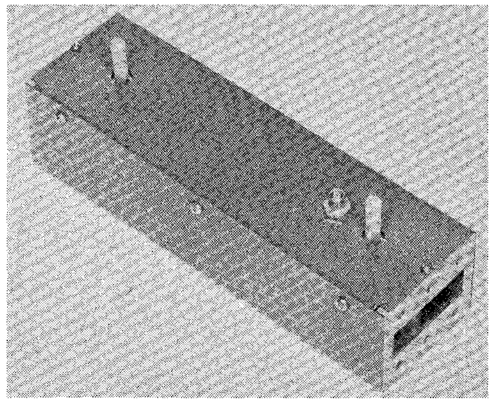

Fig. 6. The high power phase shifter. The unit provides 360° of phase shift while operating at signal levels of 115-kW peak, and 600-watts average power.

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