Recent Developments In The Average Power Capacity Of Rotary-Field Ferrite Phase Shifters

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An air-cooled experimental S-band rotary-field ferrite phase shifter with an average power capacity of 3 Kilowatts is described. The increase in average power capacity was achieved without noticeable degradation of r-f performance. An equivalent circuit model for thermal analysis is developed. The model parameters are determined by r-f and temperature measurements. The parameters are compared with those of a conventional rotary-field phase shifter.

I. Introduction

The phase characteristics of the rotary-field ferrite phase shifter are determined by the magnitude of the control currents applied to the drive coil of the phase shifter [1]. Since these may be set quite accurately, the phase shifter inherently achieves excellent phase accuracy. This, together with the relatively large peak and average power capacity of the device, has led to applications in several single-axis phase scanned antennas. The peak power capacity of garnet may be modified over a rather large range of values by either substituting for some of the iron ions [2] or by controlling the grain size of the material [3]. Because of this, power limitations on antenna design are generally imposed by the average power capacity of the phase control device.

The average power capacity of garnet devices is governed by the rate of heat removal from the material. The heat is generated by dielectric and magnetic losses in the garnet with the latter generally being the major contributor. In addition there are conductor losses in the metal waveguide walls which house the garnet material. If the temperature of the material becomes excessive, or if the thermal gradients become too large, the device will cease to operate as designed and failure—sometimes catastrophic—will occur.

The maximum reported average power capacity of an air-cooled S-band rotary-field ferrite phase shifter is 600 Watts [4], and extension of this level to 800 Watts is now routinely achieved. Higher power levels have only been reached when liquid cooling has been used, which increases cost and complexity substantially. This paper describes an air-cooled rotary-field phase shifter which operates at an average power level of 3000 Watts. This increase in average power capacity was achieved without noticeable degradation of r-f performance.

II. Average Power Capacity Limitations

A cross-section of the rotary-field phase shifter is shown in Fig. 1. A circular garnet rod and steel drive yoke are contained within an aluminum housing. Normally a finned surface is either attached to the housing or machined directly into the housing to provide increased cooling area. An equivalent circuit, useful for examining the physical limitations on average power capacity, is given in Fig. 2. Here, P_d represents the r-f power dissipated in the phase shifter, θ_r is the internal thermal resistance of the ferrite rod, θ_{sc} is the thermal resistance from rod surface to the case, and θ_{ca} is the thermal resistance from case to ambient. The quantities T_r,T_s,T_c and T_a are the temperatures of the rod, the rod surface, the case and the ambient respectively. The measurement of rod surface temperature, case temperature and ambient temperature can be accomplished easily and accurately.

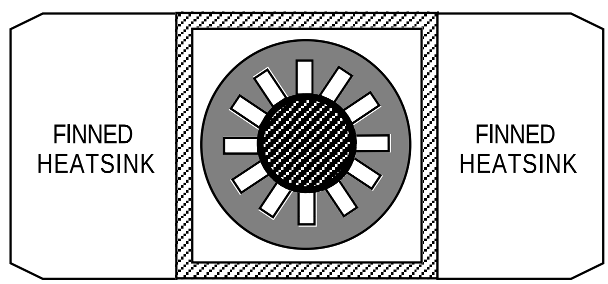

Figure 1 Cross-section of rotary-field phase shifter

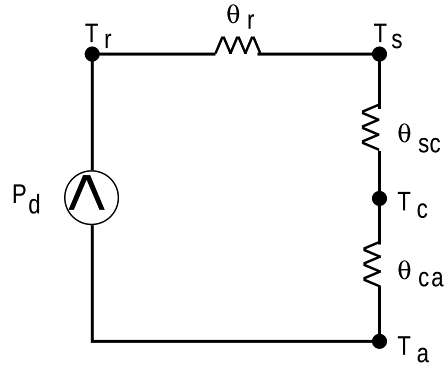

Figure 2 Equivalent circuit for thermal analysis of phase shifter

There are two different failure modes occurring as a result of heating caused by average power dissipation. The first, which may not be catastrophic, is the reduction of magnetic moment as the temperature is increased with all magnetic activity disappearing at the Curie temperature. Generally, the device will not meet its intended specifications at temperatures well below this value, since the half-wave plate is short of the design value leading to excessive insertion loss. This failure mode is affected by the ambient temperature, all the thermal resistances and the dissipated power.

The second failure—catastrophic in nature—results from thermal gradients within the garnet rod. These gradients are a function of the dissipated power, the thermal conductivity of the garnet, and the geometry of the garnet rod. If the gradients become excessive, the garnet rod fractures and failure occurs. Normally, the maximum thermal gradient is in the transverse plane and occurs at the surface of the garnet rod. However, thermal gradients may also occur along the longitudinal axis if standing waves exist in the phase shifter.

If the assumptions that 1) the rod length is large in comparison to the rod diameter and 2) the rate of heat generation is uniform [5] throughout the volume of the rod, temperture distribution within the rod may be shown to be

$$T(r) = \frac{P_d}{4\pi^2 LK}\left(a^2 - r^2\right)$$

where

- a- rod radius (meter)
- L- rod length (meter)
- r - radial distance from axis (meter)
- Pd - power dissipated in garnet volume (Watt)
- K - thermal conductivity of rod (Watt/m-°C)

From this the maximum thermal gradient may be shown to occur at the surface of the rod (r=a)

$$\left|\frac{dT}{dr}\right|_{max} = \frac{P_d}{2\pi aLK} {}^\circ C / \text{meter}$$

The thermal resistance of the rod may be found to be

$$\theta_r = \frac{-1}{P_d}\int_o^a \frac{dT}{dr} dr = \frac{1}{4\pi LK} {}^\circ C / \text{Watt}$$

III. The Experimental Phase Shifter

Periodically loading a garnet rod with low-loss material of high dielectric constant, in order to achieve operation at L-Band frequencies, has been successfully demonstrated [6]. This same technique may be used to decrease thermal gradients within the garnet rod and to increase the heat flow from the rod. Consider the segmented rod geometry shown in Fig. 3. The garnet disks are separated from one another by dielectric disks such as alumina or magnesia—two dielectric materials which have low r-f loss and thermal conductivity greater than garnet by a factor of either 3 or 4. This geometry increases the average power capacity by allowing heat to flow from the garnet to the dielectric and then to the yoke as well as the radial flow of heat directly from garnet to yoke. The internal thermal resistance of the rod is decreased substantially. Also, the thermal resistance of the rod to yoke is decreased by the factor L/L1, since the same amount of heat (approximately) is flowing over a longer length. The penalty incurred is an increase in size and weight of the unit, as well as a slight increase in the insertion loss of the device because of the power dissipated in the dielectric (less than 0.1 dB).

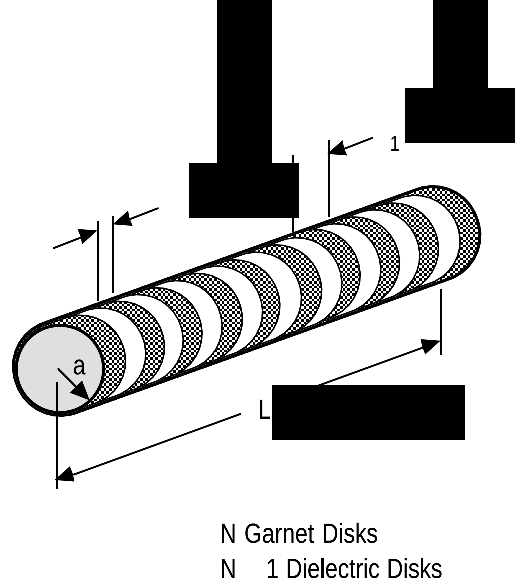

Figure 3 Garnet rod with periodic dielectric loading

The maximum thermal gradient may occur at either the flat surface or the rounded surface of the garnet disk. For the case a >> ℓ, the assumption of one-dimensional heat flow may be used with the result

$$\left|\frac{dT}{dz}\right|_{max} = \frac{P_d}{\pi a^2 L} \; \frac{\ell}{2K} {}^\circ C / \text{Meter}$$

Forming the ratio of maximum thermal gradient for the segmented rod to that of the continuous rod shows a reduction in maximum gradient by a factor ℓa.

A composite rod was formed by bonding garnet disks to magnesia disks and then grinding the assembly in a centerless grinder. The rod was placed in a thin-walled aluminum tube and matching transformers were added at both ends. The drive yoke was placed over the aluminum tube, and this assembly was placed in a finned aluminum housing. A photograph of the final configuration is shown in Fig. 4.

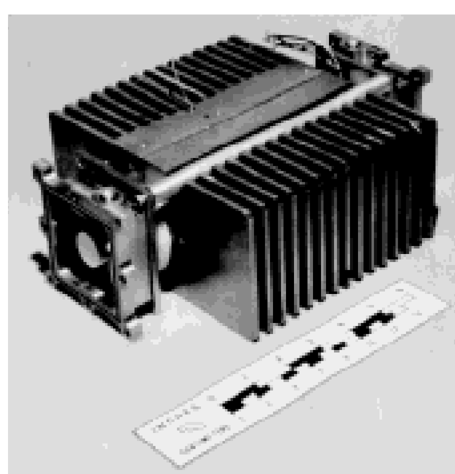

Figure 4 Photograph of experimental phase shifter

IV. Measurement Of Thermal Resistances

A temperature sensor was carefully placed on the aluminum tube of the experimental phase shifter. Another sensor was located on the phase shifter housing at the base of the cooling fins. The ambient temperature was monitored by standard means.

The temperature of the rod is impossible to measure except at the rod surface. However, the saturation magnetization of the garnet varies with temperature, causing the effective permeability to vary, which results in a variation of phase shifter insertion phase as shown in Fig. 5. Using the slope of this curve (0.526 degrees r-f per degree Celsius) and a measurement of the insertion phase, the value of average rod temperature can be readily determined.

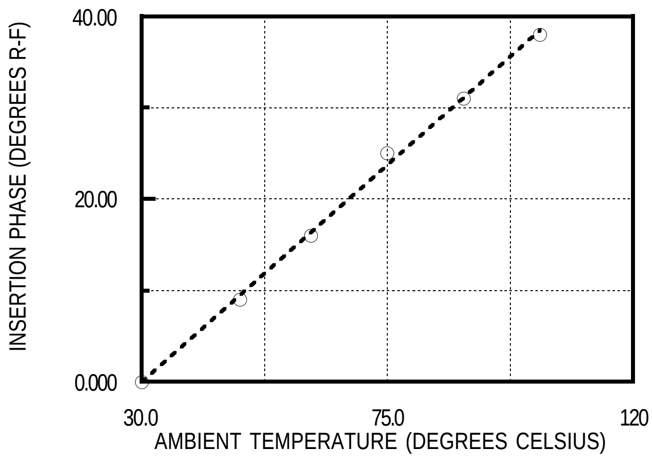

Figure 5 S-band experimental phase shifter insertion phase vs. ambient temperature

Fig. 6 gives the variation in the rod surface temperature and case temperature as a function of the average input power. Both temperatures were normalized by subtracting the ambient temperature. For a 0.5 dB insertion loss, the dissipated power is 11 percent of the input power. Using these figures, the thermal resistance θ_{sc} may be calculated to be 61°C/KW and the case-to-ambient thermal resistance to be 39°C/KW. The removal of the cooling fan increases θ_{ca} to 121°C/KW.

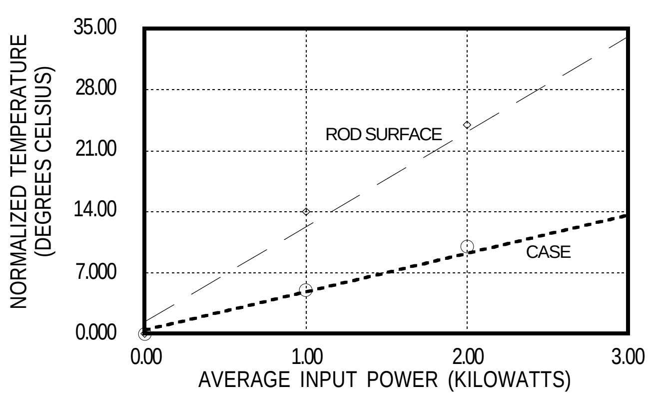

Figure 6 S-band Experimental Phase Shifter Normalized Rod Temperature vs. Average Input Power

The insertion phase increased 24.5 electrical degrees as the average power was increased from 0 to 3000 Watts. This corresponds to a rod temperature increase of 46.6°C from ambient. The increase in rod surface temperature was 33°C so that the thermal resistance q_r may be calculated to be 40°C/KW.

It is of interest to compare the values of the thermal resistances obtained for the experimental phase shifter with thermal resistances of the conventional rotary-field phase shifter. The conventional model tested exhibited an insertion phase change of 27 electrical degrees when operated at rated average power of 800 Watts. This corresponds to a rod temperature 48°C above the ambient. The rod temperature increase as a function of the average input power is shown in Fig. 7 for both phase shifters. The calculated thermal resistance of the rod is 250°C/KW, compared with a measured value of 222°C/KW. This contrasts with 40°C/KW for the segmented rod of the experimental phase shifter. The rod surface-to-case thermal resistance of the standard unit was 234°C/KW, compared with 36°C/KW for the experimental device. The case-to-ambient thermal resistance of the standard unit was 136°C/KW, compared with 39°C/KW for the experimental unit. This last value is not really surprising, since the experimental device incorporated a significantly larger finned area.

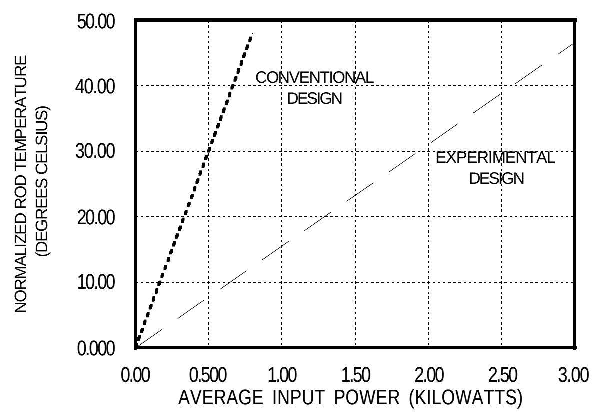

Figure 7 Temperature increase vs. average input power for conventional design and for the experimental design

V. Conclusions

An air-cooled experimental S-band rotary-field ferrite phase shifter capable of operation at an average power level of 3000 Watts has been described. Low power measurements verified the low insertion loss and excellent phase accuracy characteristic of the rotary-field device. A theoretical model for thermal analysis was developed, and the model parameters were quantified. Comparison of the model parameters with those of a conventional rotary-field device were made, and substantial reduction in the thermal resistances of the experimental unit were noted.

The technique described to enhance the average power capacity of the phase shifter may be extended to even higher average power levels than those described in this paper. By reducing the thickness of both the ferrite and dielectric disks, the surface area for cooling is increased. Further analysis on the segmented rod remains to be done to optimize the ratio of ferrite disk thickness to dielectric disk thickness from the viewpoint of both heat removal capability and thermal gradient minimization.

VI. Acknowledgements

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VII. References

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