A Method of Fabrication for Waveguide Nonreciprocal Toroidal Ferrite Phasers

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***Abstract*—An improved technique for latching ferrite-phaser construction is described. It is particularly attractive when magnetostrictive ferrites or garnets are employed and for configurations utilizing high-dielectric-constant loading. The technique is capable of yielding phasers with very uniform characteristics, large figures of merit, low loss, and excellent average power capability.**

In this short paper we describe a novel fabrication procedure for nonreciprocal toroidal ferrite phasers and report electrical measurements on ten such devices. The following are major advantages of this construction technique. 1) It can accommodate the mechanical tolerances of "as-fired" tunnel-kiln-sintered toroids. 2) The method of retaining the toroid is such that mechanical stresses due to the waveguide housing, which can adversely affect the remanent magnetization of magnetostrictive ferrites or garnets, are eliminated. 3) It minimizes the residual air gap between toroid and waveguide broad walls, which is known to act as a source of coupling to spurious higher order modes and the TEM coaxial mode associated with the switching wire. 4) A uniformly low insertion loss is obtained over a greater than 10-percent bandwidth with freedom from insertion loss spikes, a correspondingly large figure of merit, and excellent average power-handling capability.

The construction technique to be described is useful for phaser assembly regardless of the specific operating frequency range for the device. It is particularly attractive, however, for *C*-band and lower frequencies where gadolinium–aluminum doped garnet, rather than the less expensive magnesium–manganese ferrite, is often used in order to obtain the desired remanent magnetization with adequate temperature stability. It also is very advantageous for configurations utilizing high-dielectric-constant loading of the toroid insert [1]. Such configurations are quite prone to spurious insertion-loss spikes due to undesired mode coupling.

The essential details of the phaser construction are shown in Fig. 1. The ferrite or garnet toroid is located symmetrically on the axis of the waveguide and is held in position with a high-conductivity silver-loaded epoxy. The use of a conductive epoxy for phaser construction was first described by Temme *et al.* [2]. In this earlier work, the toroid material was magnesium–manganese ferrite, which exhibits very little magnetostriction. With garnet toroids the stress induced in the toroid via the epoxy-curing process adversely affects the remanent magnetization M_r. The curing is carried out at elevated temperatures (1 h at 100°C in this case), during which the epoxy hardens. On cooling to room temperature the differential contraction of the metal housing, epoxy, and garnet results in a combination of shear and tensile stress applied to the toroid. Manganese doping has been used to reduce the magnetostrictive sensitivity of garnets [3]. It has been found that for many compositions, 0.09-Mn^{3+} ions per chemical formula more or less eliminates the sensitivity to stresses applied parallel to the direction of M_r. However, there is still some sensitivity to transverse stresses. Even for these improved materials, variations in M_r due to epoxy-induced stresses can be as great as 40 percent.

The use of an indium-foil layer between the epoxy and toroid has been used to relieve such stresses [1], but from practical considerations it is not a convenient solution. The process of bonding the indium to the toroid surface is time-consuming and it is difficult to eliminate entirely residual air bubbles at the interface. In the present work the major innovation is the use of a fluorocarbon mold release compound,[1] which eliminates the need for the indium-foil strip and hence reduces phaser assembly time. Those parts of the toroid surface which would make contact with the conductive epoxy are sprayed with mold-release agent. It appears that the resulting thin film inhibits "wetting" of the toroid surface by the epoxy, and thus the undesirable shear stresses are avoided and the air gap is eliminated.

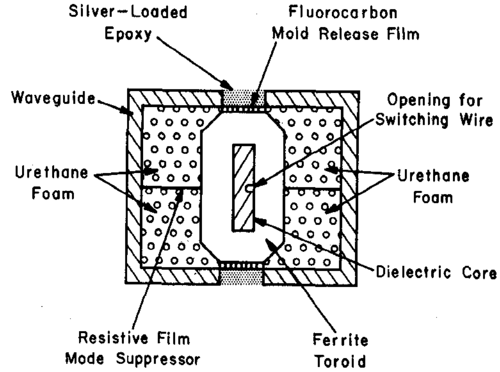

Fig. 1. Cross-sectional view showing details of phaser construction.

In addition to the moding problem, an air gap causes a longitudinal component of the RF electric field, and the accompanying current flow can result in a marked increase in insertion loss. Experimentally it is found that in order to avoid these problems, the gap should be significantly less than 1 mil in thickness. Typically, the fluorocarbon film thickness is roughly 10^{-4} in. Immediately after application, the surface of the film is polished by hand. For final assembly the toroid is positioned in the waveguide using polyurethane foam spacers, as illustrated in Fig. 1. The conductive epoxy is introduced through slots in the waveguide walls. The spacers also act as supports for resistive film mode suppressors, which ensure that any resonances due to residual coupling to the unwanted coaxial mode are damped. The mode suppressors extend beyond the toroid and overlap the ends of the switching wire. For the actual phasers constructed in this investigation, the first two higher order waveguide modes, i.e., the LSE_{11} and LSM_{11} modes [4], are below cutoff [5].

Ten phasers were assembled, having the cross-sectional dimensions given in Table I, for *S*-band operation. Our objective was to obtain a reproducible, low-cost design having an insertion loss of approximately 0.5 dB or less per 360° of differential phase shift, free from spurious insertion-loss spikes. In addition, a peak power capability of about 5 kW and incident average power capability of approximately 200 W was required. The phaser configuration utilizes a low-moment manganese-doped gadolinium–aluminum-substituted garnet ($4\pi M_s = 550$ G) toroid material. The gadolinium substitution was required to meet the peak power specification, as well as to provide some temperature compensation for the magnetization. The choice of a low-moment material, such that the condition $(\gamma 4\pi M_s/\omega_0) \leq 0.5$ is met, ensures a low value of $\mu''(\approx 0.002)$. Here, γ is the gyromagnetic ratio and ω_0 is the frequency at band center. Assuming fixed dielectric-loss tangents for the dielectric insert and the toroid, there is a particular value of $(\gamma 4\pi M_s/\omega_0)$ which maximizes the figure of merit. With conventional dielectric loading, it may not be acceptable to utilize this optimum value because of the resulting low phase shift per unit length. This objection has been removed in the present work with high dielectric constant ($\epsilon' \approx 38$) loading of the toroid slot [1]. A 4-bit digital–analog flux drive circuit [6] was used to set phase, utilizing a single control wire. A total toroid length of 7 in was chosen merely for experimental convenience. The mean value of differential phase shift for the ten phasers (measured by switching the magnetization between major *B-H* loop remanent states) is 452°.

The available stock toroids used for this work were somewhat oversized in height compared to the waveguide height (0.620 in) and were machined down. This machining operation caused variations in toroid-to-toroid wall thickness. Consequently, the insertion phase and differential phase shift spreads are larger than would be obtained with correctly dimensioned "as-fired" tunnel-kiln-sintered toroids. Notwithstanding, the rms deviation in insertion phase is only 22°. The observed small rms deviation in differential phase shift indicates the stress-free nature of the toroid fixture.

It should be emphasized that the machining operation was merely a practical expedient. Experimentation has shown that the action of the mold release agent does not depend on a smooth surface finish. The fluorocarbon compound also works well with unfinished toroids.

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[1] A release agent for epoxy potting, molding plastics, etc., type MS-122, available from Miller-Stephenson Chemical Co.

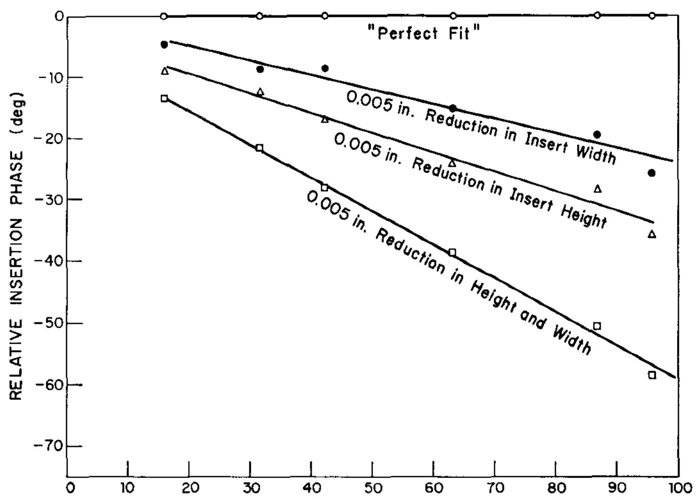
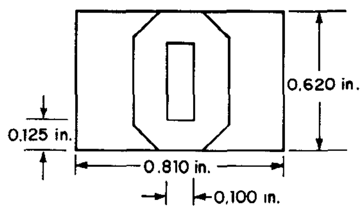


Fig. 2. Relative insertion phase versus dielectric constant for a 2-in long demagnetized garnet toroid. Toroid and waveguide dimensions are as given in Table I. Frequency =2.95 GHz.

TABLE I
S-BAND PHASER PERFORMANCE[a]

Toroid Material	G-500 + Mn^{3+}
B_r	415 G
Dielectric Constant of Insert	≈38
Toroid Length	7-in. total
rms Variation in Insertion Phase	22 deg
Differential Phase Shift, $\Delta\phi$	452 deg[b]
rms Variation in $\Delta\phi$	17 deg
rms Error of Any Bit Setting, Using 4-Bit Digital Flux Drive	<3 deg
Figure of Merit (deg per dB loss)	≈720
Maximum Peak Power (instability threshold) F = 2.8 GHz	7 kW
Maximum Average Power (a) With unidirectional conduction cooling	350 W
(b) Conduction – convection cooling	500 W

[a] Frequency is 3.0 GHz except where specified.
[b] Magnetization switched between major B-H loop remanent states.



A study was made of the dimensional tolerances of the "as-fired" tunnel-kiln-sintered garnet toroids used in this work. It was found that although the toroid wall thickness was fabricated to close tolerances (roughly 1 mil), the axial warpage over the length of the toroid was considerable. Another more serious effect was distension of the insert slot within the toroid. Thus in some cases, although an insert appeared to fit well, at certain interior locations there was an air gap as large as 0.01 in between insert and toroid. In addition to the serious moding problem, such gaps cause wide variations in unit-to-unit insertion phase. For example, Fig. 2 shows insertion phase data for a demagnetized garnet toroid, measured with a number of different insert materials. For each material, four different sizes of insert were used: 1) as near as possible to a perfect fit, 2) 0.005-in undersize height, 3) 0.005-in undersize in width, 4) 0.005-in undersize in both height and width. Evidently, the reduction in height would result in an insertion phase variation of at least 40° per 360° of differential phase shift. Hence in order to accommodate the slot tolerances of these "as-fired" toroids, the chosen remedy was to synthesize the desired toroid length with several short sections, since the overall warpage and distension effects appeared to be much less for these cascaded short pieces. In this work, the desired 7-in toroid length was composed of three shorter sections.

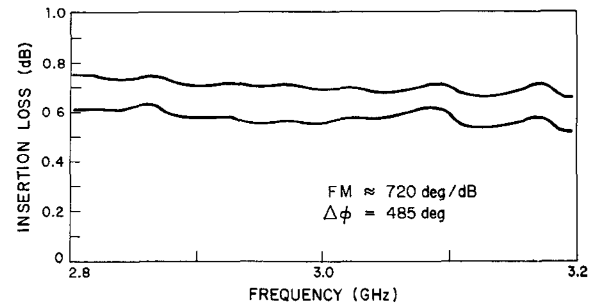


Fig. 3. Insertion loss as a function of frequency for a typical phaser. The two curves correspond to the major B-H loop remanent points ($H=0$). The upper curve corresponds to the short (B_r^+) state. The loss measurement includes the contributions of two quarter-wave dielectric transformers and two 3-step waveguide transformers.

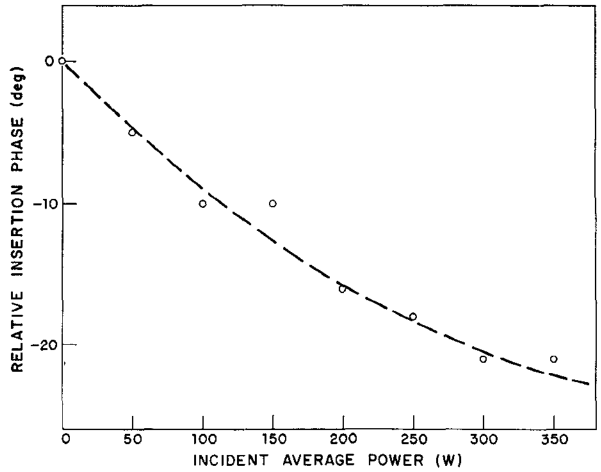


Fig. 4. Relative insertion phase of phaser versus incident average power. The toroid induction corresponds to the less temperature-sensitive major B-H loop remanent state, i.e., the long (B_r^-) state.

The insertion loss of a typical phaser over the frequency range 2.8–3.2 GHz is shown in Fig. 3. Normalized to 360° of differential phase shift the mean insertion losses for the long and short states are 0.45 and 0.55 dB. The magnetic-loss contributions are approximately 0.15 and 0.25 dB, respectively. There is no evidence of spurious insertion-loss spikes. The residual VSWR over the stated frequency range is typically less than 1.2:1.

The relatively low insertion loss of this design implies a good average power capability. Average power testing was carried out with the phaser thermally insulated to simulate the environment that might exist in a constrained feed array [7]. The heat transfer took place primarily through unidirectional conduction cooling via the waveguide aluminum housing (wall thickness 0.140 in) to a heat sink at ambient temperature. Fig. 4 shows the insertion phase as a function of incident average power at a frequency of 3 GHz, with the remanent induction set to the major B-H loop reference state (i.e., the long state). At the maximum housing temperature of 150°F, corresponding to 350 W of incident average power, the change in insertion phase was only 20°. When, in addition to conduction cooling, air convection was permitted, these temperature and insertion phase excursions were not reached until the average power exceeded 500 W.

In conclusion, we have described a method of fabrication for nonreciprocal ferrite (garnet) phasers which should be capable of yielding very uniform electrical characteristics in production. Using quantity manufacturing techniques, such as die-casting and sheet-metal stamping for fabricating the waveguide housing and tunnel-kiln sintering for producing short (i.e., 3-in) toroids, this fabrication method could yield reproducible high-figure-of-merit phasers at low cost. In addition to low cost, another attractive feature of die-casting is the ability to manufacture waveguide housings with thick walls for high average power applications. Die-cast techniques for producing a waveguide channel, with an auxiliary stamping process for manufacturing the waveguide lid, have been investigated, and a successful production run of 300 housings has been made.

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Letters

Comments on "Applications of Time-Domain Metrology to the Automation of Broad-Band Microwave Measurements"

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At the suggestion of E. H. Fooks of the University of New South Wales in Australia, we would like to comment on the errors involved in the time-domain metrology measurement techniques[1] as applied to measuring the electrical properties of materials. Mr. Fooks pointed out that the negative values of μ_r'' which are given in fig. 8 produce amplification of the signal. Obviously some experimental error is present.

At the high-frequency end of the spectrum, the errors are caused by the decrease in the signal-to-noise ratio as demonstrated by fig. 3. At the low-frequency end of the spectrum, there are two significant sources of error. First, the sample size becomes a small fraction of a wavelength so that the reflected energy at low frequencies is small. Second, the time window may be truncated before the recorded signal has reached its final value. For the spectrum of the measurement presented in fig. 8 these extremes are estimated to occur above 8 GHz and below 0.8 GHz, respectively. In the intervening region, it has been estimated that the values presented are accurate to within an absolute value of 0.1 of the measured value. Since it is well known that $\mu_r''>0$ and $\epsilon_r''>0$, one can only conclude from fig. 8 that $|\mu_r''|<0.1$.

Clearly, the particular time-domain method described is better suited to accurate loss tangents measurements on high-loss materials than on low-loss materials. It has been usefully applied to lossy dielectrics and ferrites. Other time-domain methods for low-loss materials are currently under study.

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