Round Table Discussion on Design Limitations of Microwave Ferrite Devices

THE 1957 Annual PGMTT Meeting concluded on May 10 with a round table discussion on Design Limitations of Microwave Ferrite Devices. This discussion was moderated by Professor C. L. Hogan of Harvard University, and the panel members were Drs. J. O. Artman, H. J. Carlin, D. L. Fresh, G. S. Heller, R. C. LeCraw, H. Seidel, and P. H. Vartanian. The topics considered appropriate for discussion were: 1) high-power effects (nonlinearity), 2) low-frequency limits, 3) high-frequency limits, 4) anomalous propagation in ferrite loaded waveguides, 5) below-saturation behavior of ferrites, 6) "fast" ferrite devices (depending on relaxation time), 7) bandwidth problems, 8) materials and losses, and 9) high-speed magnetic field problems. An edited version of the recorded discussion is published on the following pages.

Dr. C. L. Hogan: Gentlemen, we now come to the close of a most interesting two-day session on the present state of the art in microwave ferrite devices. In this closing session I have with me on the platform seven experts in this field who have come prepared to discuss the various aspects of this subject and to answer, as well as they are able, any questions which you might like to put to them. (Seven panel members introduced to audience.)

Dr. B. Lax (M.I.T. Lincoln Laboratory): What are some of the low-frequency limitations of garnets as compared with ferrites?

Dr. Hogan: I believe that some of the potentialities of the yttrium garnet material at the low microwave frequencies are evident from Mr. Rodrigue's talk yesterday. The fundamental low-frequency limit of any nonreciprocal microwave ferrite device is related to the "width" of the ferromagnetic resonance line. To be sure, there are several practical low-frequency problems in addition to the problem of obtaining narrower resonance lines, but assuming for the moment that these problems can be solved, we find that the ultimate low-frequency limit is set by the line width of the material. In fact, one can easily calculate the highest front to back ratio that can be obtained in an isolator using a particular material from the line width of the material and the frequency of operation of the isolator. For a given material, the theoretical reverse to forward ratio of an isolator decreases as the frequency decreases. These calculations show that a line width less than 50 oersteds is required if a 10-db isolation per 1-db insertion loss is desired at approximately 200 mc. Thus, the yttrium garnet material promises to extend the low-frequency limit materially.

However, this narrow line creates a problem in itself. Suhl's theory of nonlinear effects in ferrites indicates that the narrower the resonance line, the lower the power level at which nonlinearities set in. Hence, even though garnets promise to make possible the extension of the low-frequency limit down to a few hundred megacycles, there will be many problems associated with their use at high power levels, and one will not have as much freedom in the choice of biasing magnetic fields and geometries as one has at higher frequencies with ferrites.

Dr. P. H. Vartanian, Jr. (Microwave Engineering Laboratories): I think it should be pointed out that, excluding several of the broader line width materials, the garnet materials, as discussed in Mr. Rodrigue's paper, have, for the most part, saturation moments which are comparable to those exhibited by ferrites. For example, yttrium garnet has a saturation magnetization of approximately 1670 Gauss at room temperature. It is well known from considerations of Kittel's equation that certain geometries, such as longitudinally magnetized rods, cannot be used at low frequencies at or below ferromagnetic resonance unless the saturation moment of the ferrite is reduced. Consequently, geometry remains as one of the practical low-frequency problems. For example, a Faraday rotator using a rod of yttrium garnet cannot be made to operate below ferromagnetic resonance in *L* band. I think that low-frequency applications of garnets as well as ferrites will be limited for the most part to transversely magnetized slab geometry.

Dr. J. O. Artman (Harvard University): I would like to add that the low-field loss phenomenon is always present in these magnitudes of fields. Off-hand, I presume that the results will be pretty much the same in garnets as in ferrites and this ultimately will set a lower frequency limit in some kinds of devices.

Dr. Hogan: There is no reason why the saturation moment, and perhaps even the line width of a polycrystalline garnet, cannot be controlled by chemical methods in the same way as it is done in ferrites by adding aluminum and cobalt, as reported by Mr. Pippin yesterday.

Dr. G. S. Heller (M.I.T. Lincoln Laboratory): I would like to make another comment on this. The ferrite which I described, having a large back to front ratio at 1300 mc, had a saturation moment of 1160 Gauss and this is certainly not very low. In designing a resonance isolator the geometry helps you. Since a very thin flat slab can raise the ferromagnetic resonant frequency very substantially and minimize low-field losses, it might not be too essential in some applications to get the saturation moment down to very low values.

Dr. Artman: If I may make one additional comment, one very nice thing about garnets is that the degree of valence is unambiguous; the ions are trivalent, and presumably, some of the other loss mechanisms that may exist in ferrites can not occur in the garnets.

Dr. Howard Scharfman (Raytheon Manufacturing Co.): Is it necessary to use very low anisotropy ferrites with such structures? As Dr. Heller pointed out, good performance in resonance isolators is possible at low frequencies by using high saturation magnetization ferrites with anisotropy fields of a few hundred oersteds.

Dr. Hogan: The yttrium garnet probably has a lower anisotropy than any ferrite except those that have Curie temperatures around room temperature. Yesterday Mr. Rodrigue pointed out that by using a mixture of holmium yttrium garnet, it is theoretically possible to get a zero anisotropy material. How well this will be realized rests upon experimental evidence.

T. N. Anderson (Airtron, Inc.): What is the lowest practical frequency limit for devices that has been reached so far using conventional ferrite materials?

Dr. Heller: Well, the best I have heard done is the S-band circulator made at Sperry, operating above resonance. I don't quite know what you mean by existing ferrites, but I believe this was an aluminate which has a low saturation moment. This isolator was built to work above resonance to get out of the zero field loss region and, of course, it makes the structure quite long, which likely increases the insertion loss. If one of the gentlemen from Sperry is here, perhaps he can answer it.

B. J. Duncan (Sperry Gyroscope Co.): In relation to this device, I will have to speak in complete generalities because it is classified by the military. I was quite interested, however, that the news got around so fast. I am somewhat inclined to take issue with the statement that it has to be very long. As far as the physical structure of the Sperry circulator is concerned, it's not a particularly short device, but if one considers the operating frequency it's not appreciably longer than a similar type X-band circulator operating below resonance. We did a little work with dielectrics to improve nonreciprocal phase shift, both per unit length and per unit loss, over that attainable with ferrites alone. The techniques utilized are similar to those described earlier by M. T. Weiss of Bell Labs. I think that about all I can say about its design features is that it is a device designed to operate above resonance. Undoubtedly everyone here knows that it is a high-power device, and that it has operated successfully over a moderate bandwidth in the S-band region.

Dr. E. Wantuch (Airtron, Inc.): I have tried to operate differential phase shift circulators below resonance and the lowest frequency that I have been able to design so far is around 5000 mc (C band). It operates below resonance and the geometry was optimized according to some of the comments made a few minutes ago. As far as resonance isolators are concerned, we have to separate them into high- and low-power. For military equipment in the low-frequency region, it goes without saying that most of these applications operate at fairly high power. You probably have all seen the picture that Ben Lax presented of Airtron's 10-inch long S-band resonance isolator capable of operation at the highest available S-band power, about 5 megw peak and 4000 watts average. I know that some of the people at Raytheon have been doing work on an L-band isolator and I think we should get Howard Scharfman up here to see whether he cares to say anything about it.

Dr. Scharfman: This is prerelease information, but it is true that Raytheon has successfully built an L-band isolator with a 10 to 1 back to front ratio. The unit handles peak power in excess of 1 megw and has a power absorption capability in excess of 300 watts average. These are minimum figures and I am sure the unit can handle more. Detailed specifications will be released very soon.

Dr. Wantuch: We have also worked on coaxial isolators with the help of Microwave Engineering Labs. and have successfully made coaxial isolators down to 1800 mc. These are not what you might call extremely high-power devices, but I think they would probably compare in power handling capabilities with the 1300-mc isolator that G. S. Heller has described.

Dr. Lax: A discussion on the nonlinear effects appears to be in order. In particular, I would be interested in hearing from Dr. Seidel on how such effects would influence his anomalous propagation where he claims there are high concentrations of electromagnetic fields.

Dr. H. Seidel (Bell Telephone Laboratories): As I indicated yesterday, we have examined some of these interference phenomena with respect to the application of high power and we certainly were able to disturb the appearance of these interferences significantly with rather small magnitudes of "high" power. I hope no one will object to my ambiguous choice of words, but I believe that the major point to Dr. Lax's question is that in these modes practically all the energy density of the guide is essentially bound to a surface with a consequent large enhancement of the magnetic field there. One finds, in fact, that the higher these modes are in mode number the more the tendency to confine the wave to the surface and, therefore, the greater the tendency for loss. Hence this leads to the statements I made earlier, that one can drive a ferrite, however "lossless," into an arbitrarily high state of loss.

The same mechanisms which drive the ferrite into this very high magnetic field state are obviously the same mechanisms which can induce the high power effects; and we have observed them. However, since these waves are so highly bound at the surface, there is a question of how far the high-power phenomenon will propagate transversely within the ferrite beyond this very high density region. So far I don't have any information about this, although it would be rather interesting to determine whether these very highly concentrated fields can possibly nucleate high-power effects into the interior of the ferrite at powers lower than those for which they occur ordinarily.

Dr. R. C. LeCraw (Diamond Ordnance Fuze Laboratories): I would like to ask one of the members of the panel a question. I was under the impression that one of the possible advantages of the type of isolator you have been suggesting is that, in contrast with displacement isolators utilizing a resistance strip, the power would be dissipated within the entire volume of the ferrite rather than in a small thin strip. But did you not indicate that this is a surface phenomenon and that all the power dissipation would take place on the surface of the ferrite?

Dr. Seidel: Power dissipation does occur on the surface; however, one can get these propagations in arbitrarily small guide so that there need not be much more ferrite than just the surface. I believe that the ferrite can be made sufficiently small to produce these effects. There isn't too much of a heat transmission problem, I believe, because of the finite manner in which the energy is bound to a surface. It will have considerably higher power dissipation than a very thin film, but I am not sure just how much power one should actually attempt to dissipate.

Dr. H. J. Carlin (Polytechnic Institute of Brooklyn): I would like to ask whether it had been definitely established that some of this anomalous propagation could not be described by a complete set of TE and/or TM modes, that is, an ordinary mode description, and whether it was necessary to assume that this anomalous type of surface mode was necessary?

Dr. Seidel: I would say that these anomalous modes are part of a complete set and not an admixture of another part of a complete set. These modes will propagate under conditions where no other modes can propagate and one can ascribe propagation constants to these field distributions which are real. Since real propagation constants cannot be obtained from an admixture of cutoff modes, we must conclude that these anomalous modes are a linearly independent portion of a complete set.

Dr. Lax: There is one thing that disturbs me about this type of propagation. You are talking about it when the field is adjusted for resonance. I presume that, when you were talking about these high reverse-to-forward ratios due to bridging effects, you were on resonance.

Dr. Seidel: These are nonresonant effects which operate at relatively low fields, and these are not interference phenomena. They differ from the bridging phenomenon Crowe alluded to yesterday.

Dr. Lax: Nevertheless, one does obtain a large loss factor at these particular frequencies.

Dr. Seidel: We have built various types of "paradox isolators" (I guess that's as good a name for them as any, I was even thinking of using the name "Laxadox isolators") and actually we get fairly low losses in one direction and rather wide rejection of nominally large values in the opposed direction, essentially without reflection. I would like to elaborate, just for a moment, on what I feel might be the primary advantage of such devices. Resonance isolators, field displacement isolators, or the type of isolators that Bill Crowe talked about yesterday, depend on balancing techniques or circuit resonance. These are effects which can only be stimulated over a narrow band. The field displacement isolator is a device operating over a limited band where the field is essentially excluded from a dissipative medium. Faraday devices operating dispersively would tend to act this way too. The virtue of the sort of isolator which you have introduced in paradox form, Dr. Lax, is that the isolation occurs in principle over a very broad range, whereas transmission over this range is not restricted. I believe, therefore, that we may possibly be able to build relatively broad-band devices based on this sort of phenomenon, as opposed to the type of isolator which one builds on the other effects, namely operating on a balance which is theoretically perfect at only one frequency.

We have built some rather striking isolators based on these phenomena, although these are as yet not nearly as wideband or as lossless as I would hope. I feel that these structures represent not so much of an anomaly as a rather interesting and practical sort of mechanism for construction.

Dr. Vartanian: I wonder if Dr. Seidel would care to comment on the relationship between this anomalous propagation and the spinwave modes described by Suhl and Walker. Is there some kind of relationship between these two phenomena?

Dr. Seidel: It's unfair to call them the Suhl and Walker modes because in this particular area Suhl obtained one set of spinwave modes, Walker obtained another, and I believe I have obtained still another. Suhl involved himself with spinwave modes which relate to the exchange system and these are of extremely high wave numbers. I do not believe that the sort of modes which we get in the anomalous propagation relates to them. These modes may have wave numbers of the order of a micron wave length, which are of the order of crystallite dimensions and, therefore of the order of many thousands of lattice constants. On the other hand, the Suhl type of mode actually gets down to just the order of several lattice constants and it is of entirely different nature. Walker's modes I believe are somewhat similar to my own, except, that he treats them in a localized region. He shows that there are transversely propagating modes within a disk or sphere or some limited geometry. The modes I have referred to as "anomalous modes" are somewhat reminiscent of Walker's, but relate to a cylindrical waveguide distribution. Mechanisms dealt with are similar; Walker and I both employ only the dipolar features associated with the ferrite and do not consider its exchange.

Dr. R. F. Soohoo (Cascade Research Corp.): If we assume both the waveguide and ferrite to be lossless, would the anomalous mode still have loss in it? Do you still have energy dissipated, and if so, where does the energy go?

Dr. Seidel: Technically, every medium must have some loss on an atomic level of description. In the treatments generally considered, an idealization is made of the medium to a continuum with a precessional character represented by the Polder tensor. Maxwell's equations are thermodynamically correct and there is no violation of thermodynamics within this framework of description of the medium in assigning a zero value to the damping parameter. I assume that the question asked relates to energy absorption in such a hypothetical medium. This type of absorption relates in turn to the Lax anomaly discussed earlier in which energy absorption might appear to occur in such an idealized dissipationless medium.

In answer to this question I feel that the "anomalous" modes represent a mechanism of energy loss in such a medium. We define a lossless medium to be a limiting case for one whose resonance line width approaches zero. Choosing any line width, however narrow, one may then always choose a mode of wave number of order greater than the reciprocal of the line width which absorbs energy from the medium. Essentially this implies that, however small the damping parameter, one may always find waves sufficiently slow to absorb energy. This description, however, fails when the wave numbers become atomistic, since they have no meaning within this sort of a description.

Philip Johnson (Signal Engineering Laboratories): During this conference there has been no discussion about the barium oxide type of magnet, in fact there hasn't been much since M. T. Weiss' paper of a few years ago. I was wondering if you think there is much hope for the barium oxide type device today?

Dr. Hogan: In the first place, it appears that all of the ferroxoplanar materials including Ferroxdure have been neglected by microwave engineers. Perhaps this is due to the fact that up to now there has not been great emphasis on the need for devices which operate at the extremely high frequencies where these materials will be most useful. There is no doubt that these materials offer unique advantages at the very high frequencies where very large magnetic fields are necessary to bias a ferrite to resonance. As a single crystal or as an oriented polycrystal, the high anisotropy fields in these materials can be used to materially reduce the applied field necessary for resonance. Since the family of ferroxoplanar materials promise to give us materials in which the anisotropy field can be controlled over wide limits, it appears that these materials will have a distinct advantage over the usual ferrites for most frequencies above K band. In addition, the limited data that has been taken on these materials indicate they can be prepared with extremely low dielectric loss.

Dr. Vartanian: I might add something to this. I believe that the Dutch at Phillips Research Laboratories are doing a considerable amount of work on this ferroxoplanar material, and about two months ago they were going to begin measuring its properties at microwave frequencies. I haven't heard anything since, however. Another interesting property of these materials seems to be that they will maintain a high permeability, which remains flat as a function of frequency all the way out to something like, say, 1200 mc. Typical values of permeability might be around 10 or so.

Dr. Artman: Another interesting thing about these materials (which may not have practical use) is that under certain simplified conditions in single crystals below magnetic saturation, the material is a gyrotropic resonator in a plane, but just a linear resonator in the third direction at a different frequency from that for gyrotropic resonance.

Leonard Swern (Sperry Gyroscope Co.): I would like to direct the panel's attention to fast switching type ferrite devices. I am wondering whether anybody can talk about, let's say, devices in the megacycle switching rate region, perhaps single-sideband modulators, and what material developments are required to really extend that region.

Dr. LeCraw: The subject of fast ferrite switching is an interesting area in which a lot of ferrite materials development needs to be done. I'm afraid, though, that your question is so broad I don't know where to start. For some of you who may not be aware of it, ferrite microwave switches have been made which can operate as fast as 5 mμsec switching time from an ON to an OFF state or vice versa. This limit was the limit of our viewing system. The actual limiting ferrite switching time is probably of the order of the spin-spin relaxation time, which is approximately 1 mμsec. But from this value all the way through the microsecond range, which you mentioned, there is a whole series of design problems. We have found that ferrites intrinsically can handle speeds as fast as 5 mμsec. From this speed range to much slower speeds one should know whether he is forced to use transverse fields or longitudinal fields, or whether he has a heavy duty cycle or low duty cycle, in order to discuss the design limitations.

I would like to say one thing further about materials development in connection with high-speed ferrite switching. I am speaking now of microwave switching and not of computers. One of the biggest problems is finding a ferrite which has good characteristics both at microwaves and over the frequency spectrum of the rise time that you are talking about. I believe very little has been done in this respect because most microwave design engineers are so concerned about insertion loss that they are unwilling to tolerate an extra db of insertion loss in order to obtain a ferrite with much lower hysteresis loss, for example, to minimize the area under one pulsing cycle.

John H. Rowen (Bell Telephone Laboratories): A switch designed at our laboratories is amenable to fast switching applications, but we were using it to switch a microwave relay where a millisecond was fast enough. I should point out that the same principle of operation was used in LeCraw's switch even earlier. LeCraw added a number of details which make it possible to produce a very fast switch. Both switches make use of an interference effect such that the current required to turn the switch off has a very broad characteristic. The switch is initially turned off, say with 100 ma of solenoid current, and stays turned off until it exceeds several hundred milliamperes. The virtue of this is that one can choose a steady-state value of current way up on the characteristic, and very early in the rising portion of the current cycle the switch will go into the OFF position. In this way you can get perhaps a factor of ten in improvement in switching time; *i.e.*, ten times the limiting speed of switching the ferrite itself. LeCraw achieved this sort of dependence in his switch through the use of irises. J. A. Weiss, through the use of different kinds of irises, has produced the same effect in a way that can lead also to a reasonably broad-band switch, for example, a switch which would operate over a band of 200 or 300 mc out of 6000 mc. However, as I said, we haven't carried out any extensive experiments on fast switching devices.

Dr. Vartanian: There is one rather basic problem to any high repetition rate ferrite switching scheme in which the direction of the magnetization is reversed or in which the ferrite is allowed to become unsaturated. This is that the hysteresis losses can cause a significant rise in the ferrite temperature which in turn can significantly degrade the switching characteristics. Consequently, it would seem desirable to operate high duty cycle switches with the ferrite remaining normally saturated, and let the switch operate as a result of a change in H rather than M.

Dr. Soohoo: I would like to say just a word about fast switching. Since the switching time or the speed at which it is switched depends among other things on the eddy currents, it seems that we have to concern ourselves with nearby metallic objects as well as the ferrite itself. For example, iron has resistivity of 10^{-5} ohm-cm while ferrite has resistivity of 10^{9} or so, which is 14 orders of magnitude higher. It seems to me the speed would be limited more by the waveguide and the winding nearby, for example, rather than by the intrinsic properties of the ferrite itself.

Dr. Wantuch: I won't go into any details here for fairly obvious reasons but we have designed ferrite switches as tr tube replacements. We have been able to switch in a tenth of a microsecond and the total power required for switching at several-hundred-kc rate has been about 10 watts average.

Dr. LeCraw: I would like to say a word about Dr. Soohoo's question. For very high-speed switches where you have to worry about skin depths and penetrations of waveguide, etc., we have had considerable success in putting the coil inside the waveguide very close to the ferrite, in fact within 1/16 of an inch of the ferrite, without appreciably perturbing the microwave fields. This is very advantageous from a pulse design standpoint and can appreciably diminish the effects of the waveguide walls and eddy currents.

Dr. Soohoo: We have built the Cacheris single-sideband modulator and found that a metallic coating on the inside of the waveguide substantially limits the field requirement. For instance, we found that a very bulky magnet was required for a K_u-band modulator.

John C. Cacheris (Diamond Ordnance Fuze Laboratories): We have designed several reflection type single-sideband modulators that shift the frequency of X-band signals by 20 kc using a magnetic field, rotating transverse to a ferrite differential half-wave section. With thin coatings of either cadmium or nickel plating we have minimized eddy current losses in the waveguide so that the rotating magnetic field is not appreciably attenuated. We have found that the ferrite, and its geometry, are the most important factors in obtaining the 180-degree differential-phase-shift with as low a value of magnetic field as possible, so that the modulating power is not too large. At X-band frequencies, the 200-oersted magnetic field can be rotated at 10 kc by applying approximately 18 watts in each pair of coils. At K_u band the magnetic field required will be larger, since the differential-phase-shift decreases with increasing frequency and the modulating power will be larger. The eddy current losses do not depend upon the microwave frequency. They depend upon the value of the magnetic field and should account for the same fraction of modulating power.

Dr. Seidel: I should like to ask Dr. Carlin a question. There are many types of representation of ferrite structures which are all equivalent. For instance, Tellegen represents the nonreciprocal character of the ferrite through a gyrator type of description. Haus has a nonreciprocal element, a four pole cascade element. Circulators are employed in describing ideal networks too. If you desire to describe a ferrite network through a minimum number of elements, what do you consider are the canonical elements for such a description?

Dr. Carlin: There are many circuit representations for linear nonreciprocal structures. For example, just recently, at the 1957 IRE National Convention, Mason presented another basic nonreciprocal element and there have been many others. So far as I know the only complete treatment of general linear nonreciprocal passive circuits in canonical configuration (*i.e.*, a treatment which shows that given any physically possible system it will always be possible to form an equivalent circuit out of preassigned building blocks) has been done in terms of usual reciprocal elements and the gyrator. With that as a basis, any other element you want to take as a building block to represent nonreciprocity must be shown capable of suitable combinations to form the equivalent of a gyrator. As to which building block is most convenient, and gives the best equivalent circuits, I don't think I would know the answer to that. I would imagine that you would have to adapt your equivalent circuit representations to the problem at hand. In some instances current and voltage controlled sources might be most useful (these are active, however). In other instances a "gain-producing" black box has been used. The gyrator however has the theoretical advantage of being purely passive, and I may reiterate that any passive linear system may be represented in terms of gyrators and conventional bilateral elements.

Dr. Seidel: Could you go into just a little more detail on Mason's equivalent circuit?

Dr. Carlin: I heard Mason discuss the so-called gyristor at the IRE 1957 National Convention and, maybe I won't do justice to him, but it was something like this. Any nonreciprocal circuit can evidence nonreciprocity if it's at least a two-port, as it must have an input and an output. For this reason no nonreciprocal element is needed to represent a one-port. However, Mason uses what appears to be a one-port for his nonreciprocal building block. This two-terminal device works as follows. If it has a voltage V_A (terminals 1 to 2). the current I_A (1 to 2) is aV_A. If the same voltage is impressed from 2 to 1, the current from 2 to 1 is not I_A but $-I_A$. If you visualize a ground terminal as terminal 3, it is easy to see that with respect to voltages to this ground reference the device has an admittance matrix $Y_{11}=-Y_{22}=a$, $Y_{12}=-Y_{21}=a$. Thus this element is actually a nonreciprocal three-terminal two-port. Furthermore, it is not passive and can be represented as a gyrator shunted by a positive and negative resistor at its input and output, respectively.

Dr. Artman: I might mention that from a physical point of view it's immediately intuitive that you should have a two-port system. If you have an ordinary type of linear oscillator there is only one direction. Here something else happens in another (a perpendicular) direction, and really everything automatically follows from that.

Mr. Cacheris: What are the limitations of a single crystal as compared to polycrystalline materials when used in devices with regard to switching time, losses, etc.?

Dr. Hogan: The question, if I understand it correctly, is, "What are the potentialities and limitations of single crystal materials as compared to polycrystalline materials for various microwave devices?" Often in the past, single crystals sounded very promising for many types of microwave devices and I know of some development work being done where single crystal ferrites were used in several devices. Usually, however, the designer finally ended up using polycrystalline material, not only because it was cheaper and more reproducible, but because the polycrystalline material could be made with most of the desired properties and there seemed to be little reason to press for better materials.

However, many of the newer devices recently proposed (*i.e.*, harmonic generators, Suhl's amplifier, microwave detectors, and passive limiters) appear to be really practical only with the very narrowest resonance line width materials available and so it does seem that in the future single crystal ferrites and garnets will have more engineering importance than they have had up to the present. Before they can be used, however, it appears that much work will need to be done on methods of preparing the single crystal material. In most of these devices we need larger, more homogeneous crystals than are usually available today.

We really can't say much else in comparison except as a conjecture, since there is little data on single crystal material. Usually single crystal ferrites have much higher dielectric loss than polycrystalline ferrites, but this need not always be the case if we can learn to grow single crystals with the proper oxygen stoichiometry. Probably the magnetization in a single crystal can never be switched as fast as it can be in some of the specially prepared polycrystalline materials.

Dr. D. L. Fresh (Trans-Tech, Inc.): The potential need of large single crystals presents a serious problem to workers in the materials field. Whereas polycrystalline ferrites can be prepared utilizing standard ceramic methods of compacting oxide mixtures and kiln firing, single crystal preparation requires tedious and time-consuming techniques, which often involve elaborate equipment. The two techniques which have been investigated most extensively are precipitation from a melt and Verneuil's method. In the precipitation method the oxide constituents are combined with a flux and the mixture is melted by heating. Upon very slow cooling, crystals precipitate from the melt. Galt at Bell Telephone Laboratories used a method employing a flux of borax to prepare crystals of nickel ferrite and zinc-manganese ferrite. Garnet single crystals have been prepared by this method using lead monoxide as a flux. The main disadvantage to the precipitation method is the small size of the product, which is usually not more than several millimeters on an edge. A second disadvantage is the possibility of inclusion of impurities from the flux. Verneuil's method offers a means for growing larger single crystals. Here the oxide mixture is shaken into the flame of an oxygen-hydrogen torch. The mixture is sintered into a cone which collects on a refractory pedestal. The top of the cone melts and the pedestal is lowered gradually as the melted material builds up and in this way a crystalline boule is formed. Due to the high temperatures required in this method, it is very difficult to establish stoichiometry from the standpoint of oxygen content and, in some instances, metal content too, if volatile metallic constituents are involved. Such nonstoichiometry generally leads to a useless product because of a high dielectric loss. Verneuil's method has been employed in preparing the spinel type of ferrite, such as magnesium ferrite, but I am not aware of any work that has been done using this method on the garnets. Such an effort might prove fruitful since the garnet crystal does not contain divalent metallic ions and therefore would be less susceptible to nonstiochiometry. If the need for large single crystals materializes, the two methods just discussed, as well as other methods such as zone melting and vapor deposition, should be thoroughly investigated. As Dr. Hogan remarked, there is definitely a lot to learn about growing single crystals before they will become available. I strongly endorse this sentiment.

Dr. Artman: I would like to make one additional comment, leaving aside the very difficult problems concerned with procuring these crystals. The analysis of many of these devices being discussed would be much more difficult because the specification of the properties of the medium would be somewhat more complicated due to the single crystal properties (which are in a sense averaged out when you speak about polycrystals). If I may, I would like to ask a question on another subject. Since the advent some years ago of ridged waveguide why, at least to my limited knowledge, have no isolators or other components been developed using this type of waveguide?

Dr. Wantuch: I would say that for ridge guide isolators you have some of the same problems you have without ridges. There is always the average power that you have to handle and I think there is nothing really different about ridged waveguide. I know we have made isolators covering 40 per cent or more in bandwidth with the same kind of ratios you have in ordinary rectangular waveguide configurations.

Dr. A. L. Aden (Sylvania Elec. Prod.): Sylvania has built isolators of several types using ridged waveguide. Using dielectric loaded ridged guide we have built isolators covering a bandwidth of 2 to 1. I think the reason that ridged waveguide is not used more commonly at the present time, however, is that the bandwidths currently achievable in rectangular waveguide structures are adequate to meet the needs of most systems applications. For example, Sylvania has built isolators with a bandwidth of 1.5 to 1 in dielectric loaded rectangular waveguide in all frequency bands from S through X band. In addition, recent, and as yet unpublished, work at the Sylvania Microwave Physics Laboratory has shown that with proper dielectric loading the bandwidth of a rectangular waveguide can be increased by a factor of approximately 1.7 over its empty waveguide bandwidth.

Dr. Seidel: I would like to ask a question of Dr. LeCraw. I know that both he and John Rowen have observed negative values of K''. Would he comment on its significance?

Dr. LeCraw: Let me say one thing first about K itself, the off-diagonal component of the permeability tensor. Some people take K as an intrinsically negative number and others take it as a positive number. This has caused some confusion as to whether the anomaly is a negative K'' or a positive K''. But either way the change of sign of K'' is the essential anomaly. There is no contradiction at all as far as absorbed power is concerned in the change of sign of K''. It is easy to show by integrating the power dissipated in a ferrite that K'' can have either sign. But μ'' cannot have either sign; it must be positive. As far as K'' changing sign, an important thing about this is that below saturation the μ and K are spatial averages of quantities which only have "point" meaning down inside a crystallite. Slides are often shown of μ and K, but below saturation these quantities don't have quite the same meaning as they do above saturation. The K'' changing sign means that the average of K'' over all the crystallites in the sample changes sign. These averages, of course, are the experimental quantities which are measured in any perturbation experiment. But it is a rather interesting effect in that below saturation the anti-Larmor sense of circular polarization is in general absorbed to a greater extent than the Larmor sense of polarization. Incidentally, the change in sign of K'' below saturation is an intrinsic loss property of the ferrite and should not be confused with the widely discussed energy concentration effects in the experiments of A. G. Fox of the Bell Telephone Laboratories. The situation reverses above saturation and everything is normal from then on out to arbitrarily large dc fields. The explanation of the effect is rather involved, and I hope it has been explained satisfactorily in an article which I have written recently. The effect should be very useful as a probe for studying domain structure and magnetization processes in ferrites.

Dr. Artman: I would like to make one slight comment; I think it's a little bit unfair to single out K'' as such. Again, going back to the basic model, the ferrite is a gyroscope and when you consider loss you have to consider gyroscopic precession. If you have some kind of a linear drive you have to, at least visually, break up the drive appropriately into two gyroscopic drives. True, on a glib basis some of these μ'' and K'' may drop out or something like that, depending upon the circumstances, but I think it would be best to keep, or try and keep, the physical picture in mind.

E. Schlomann (Raytheon Manufacturing Co.): I wonder if somebody could comment on the relative advantages and disadvantages of the new garnet amplifier and the solid-state maser.

Dr. H. E. D. Scovil (Bell Telephone Laboratories): At the moment both devices would appear to be quite expensive amplifiers *per se*, and it would seem that perhaps the main virtue of them would be what we hope is a low noise figure. At the present time the noise figures have not been measured.

There is good theoretical reason to believe that a two-state maser has low noise. Perhaps one should be somewhat more cautious with regard to the three-level solid-state device in so far as the large pumping power may mix in noise from some unknown nonlinearities. The ferrite device being essentially a reactive amplifier at first sight also has low noise; on the other hand there appears to be perhaps even a stronger possibility of mixing in additional noise. We must await the noise measurements.

The ferrite device is capable of higher output powers than the maser and operates at room temperature. At the present stage the solid-state masers are low temperature devices.

Mr. Anderson: Could we get some suggestions for nomenclatures for these devices, three-level maser, two-level maser, the ferrite or garnet amplifier, so that maybe we could start using a common name?

Dr. Scovil: I believe the term "maser" should be restricted to devices utilizing a population inversion or negative temperature and that the various masers should be differentiated perhaps by a prefix indicating their method of operation; *e.g.*, ammonia beam maser, two-level maser, three-level maser, etc.

I think that the christening of the ferrite device is best left to Drs. Suhl and Weiss who have produced it. It does not fall in the category of negative temperature devices.

Dr. R. W. Damon (General Electric Co.): The principal reason for the great interest in resonance amplification devices lies in their potentiality as low noise amplifiers. Usually the term "noise" refers only to a fluctuating output observed in the absence of a signal, but, under some conditions, random variations in amplifier gain also should be considered. In this respect, the ferromagnetic amplifier might be at some disadvantage compared to the three-level paramagnetic device. The paramagnetic amplifier uses the driving oscillator only to create a saturation condition for a pair of energy levels. If the driving power is sufficiently large, fluctuations in the driving level have little effect on the degree of saturation and the gain is thus independent of small variations in driving power. The ferromagnetic amplifier, on the other hand, operates as a negative resistance device, obtained by driving a nonlinear reactance with power level above a certain instability threshold, and fluctuations in power level of the driving source will lead to fluctuations in gain.

Dr. Hogan: Well I have just been informed that in about 3 minutes the lights in this auditorium will be turned out, so I suggest we start on our way.

Correspondence

Note on Impedance Transformations by the Isometric Circle Method*

The isometric circle method is a graphical method of transforming a complex quantity by the linear fractional transformation. It has recently been applied to impedance transformations through bilateral two-port networks.[1] The purpose of this note is to show the connection between the isometric circle method and another graphical method called the "triangular" method, and also to present a useful formula for reflection-coefficient transformations through bilateral, lossless two-port networks.

The triangular method is described in an unpublished paper by Mason.[2] In this method it is assumed that one pair of corresponding values $Z_a \rightarrow Z_a'$ is known for the linear fractional transformation

$$Z' = \frac{aZ + b}{cZ + d}, \quad ad - bc = 1 \qquad (1)$$

where, for a fixed frequency, a, b, c, and d are complex constants. The values $Z' = O_i = a/c$ for $Z = \infty$, and $Z' = \infty$ for $Z = O_d = -d/c$ are known also. For an arbitrary impedance Z, the transformed impedance Z' is constructed by drawing the similar triangles O_dZ_aZ and $O_iZ'Z_a'$ in the complex impedance plane. See Fig. 1. The connection between the triangular method and the isometric circle method is shown in Fig. 1. In Fig. 1, the different operations of the isometric circle method (marked by arrows) are indicated by the points Z_1, Z_2, and Z', and the angle $-2 \arg (a+d)$ is denoted by θ.

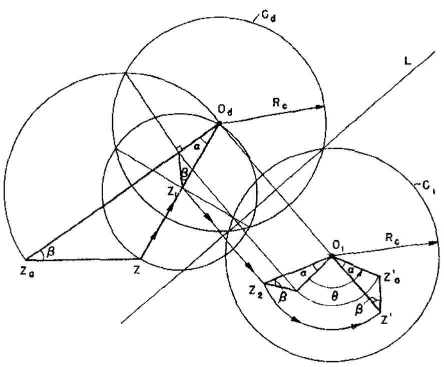

Fig. 1—Connection between the triangular method and the isometric circle method.

Impedance transformations through bilateral, lossless two-port networks can be performed by the equation

$$Z' = \frac{a'Z + jb''}{jc''Z + d'}, \quad a'd' + b''c'' = 1, \qquad (2)$$

where $a' = \text{Re } a$, $b'' = \text{Im } b$, $c'' = \text{Im } c$, and $d' = \text{Re } d$. Expressed in reflection coefficients, (2) takes the form

$$\Gamma' = \frac{A\Gamma + C^*}{C\Gamma + A^*}, \quad |A|^2 - |C|^2 = 1, \qquad (3)$$

where

$$A = (a' + d')/2 - j(b'' + c'')/2$$
$$C = (a' - d')/2 - j(b'' - c'')/2. \qquad (4)$$

A star indicates a complex conjugate quantity.

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[1] E. F. Bolinder, "Impedance and polarization-ratio transformations by a graphical method using the isometric circles," IRE Trans., vol. MTT-4, pp. 176–180; July, 1956.

[2] S. J. Mason, "A Simple Approach to Circle Diagrams"; 1954.