Correspondence

Amplitude and Phase Modulators in Rectangular Waveguides for 5 to 7 Gc/s

While investigating the electrical and magnetic properties of ferrimagnetic materials, Reggia and Spencer [1] discovered that it was possible to obtain very large reciprocal phase shifts with a longitudinally magnetized ferrite rod, centrally located in a standard rectangular waveguide. Since that time, many investigators [2]–[5] have continued to study (both theoretically and experimentally) the properties of this phase modulator and have since been able to design and fabricate a number of different versions of the original model. Also during this time, continued investigations at Harry Diamond Laboratories, Washington, D. C., of the RF field distribution inside these magnetized ferrite rods have led to the discovery [6]–[8] of a new type of amplitude modulator (or absorption modulator) with electrical characteristics particularly desirable in a microwave switch. This absorption modulator-switch has a geometrical configuration very similar to that of the reciprocal phase modulator. In fact, the same waveguide and solenoid assembly is often used today for both the phase modulator- and the amplitude modulator-switch.

This correspondence discusses the design and operation of these waveguide modulators in the frequency range from 5 to 7 Gc/s. These small reciprocal ferrite modulators are generally characterized by low insertion loss, microsecond response time, matched input impedance for all values of amplitude and phase changes, and power handling capability of a few watts CW and kilowatts peak. Amplitude modulation with positive, negative, or nearly zero phase shift, and phase modulation with small amplitude modulation are also characteristic of these waveguide modulators.

Design Considerations

Beginning with the design data referred to above, and selecting a standard rectangular waveguide for the desired frequency range, it is first necessary to select a suitable ferrite material. A small dielectric and magnetic loss tangent at the operating frequency is required to obtain an amplitude or phase modulator with low insertion loss. It is then necessary to determine the minimum cross section of the ferrite to obtain sufficient concentration of microwave energy, a necessary condition for obtaining a high figure of merit. The maximum rod cross section must also be determined so that spurious RF modes are not permitted in the ferrite-loaded waveguide. Both the maximum and minimum rod cross section are critically dependent on the narrow dimensions of the rectangular waveguide.

Manuscript received August 9, 1965; revised October 18, 1965.

Impedance matching is accomplished by using linear tapers at both ends of the ferrite rod and polyfoam dielectric support. This impedance matching, along with the use of a low-loss ferrite inside a traveling-wave transmission line, accounts for the low insertion loss obtained with the waveguide modulators.

Reciprocal Phase Modulators

Cross-sectional views of the reciprocal phase modulator making use of the design techniques originally described by Reggia and Spencer [1] and Reggia [5] are shown in Fig. 1. It consists essentially of a longitudinally magnetized ferrite rod (round or square) centrally located inside a standard rectangular waveguide excited in its fundamental TE_{01} mode. A low-current solenoid, wound around the rectangular waveguide section, is used to supply the longitudinal magnetic control field.

The phase-shift and VSWR characteristics of the waveguide modulator over the 5000- to 5300-Mc/s frequency range vs. the applied magnetic field are shown in Fig. 2. A 0.500-inch diameter MgMn ferrite rod[1] was used in a 1- by 2- inch standard rectangular waveguide. Phase shifts greater than 500° were obtained with this $5\frac{1}{2}$-inch long rod (including $1\frac{1}{2}$-inch tapers at both ends) over at least a 6-percent bandwidth with a magnetic control field of less than 100 Oe. The zero-field insertion loss of this phase modulator was 0.4 dB, and the observed amplitude modulation was less than ± 0.2 dB.

The phase-shift-bandwidth characteristics of a slightly smaller ferrite rod (0.460-inch diameter, 5 inches long) in a $\frac{3}{4}$- by $1\frac{1}{2}$-inch waveguide are shown in Fig. 3. As seen in this figure, phase shifts in excess of 500° were obtained over the frequency range from 5850 to 6150 Mc/s with a magnetic control field of less than 70 Oe. These higher values of phase shift with lower magnetic control fields are due to the greater microwave energy concentration inside the ferrite rod at these frequencies. The insertion loss for this reciprocal phase modulator was less than 0.5 dB, and the input VSWR was less than 1.4 for all values of the applied field.

Similar results, described by Reggia [5], were obtained at higher waveguide frequencies to 25 Gc/s.

Absorption Modulator-Switch

As mentioned in the introduction, another application of the longitudinally magnetized ferrite rod in rectangular waveguide is to obtain a broadband amplitude modulator (or absorption modulator) with the electrical characteristics especially desirable in a microwave switch. This is accomplished by placing a very thin resistive film inside the ferrite rod so as to attenuate only the perpendicular component of the microwave field generated in the magnetized ferrite.

Cross-sectional views of the broadband absorption modulator designed according to the techniques described by Reggia [6], [8] are shown in Fig. 4. Beginning with the end view seen at the right, a relatively large rectangular ferrite rod is centrally located inside a standard waveguide by a polyfoam dielectric support. A metallized resistive film is placed in a horizontal plane (perpendicular to the input RF electric field) at the center of this tapered ferrite rod.

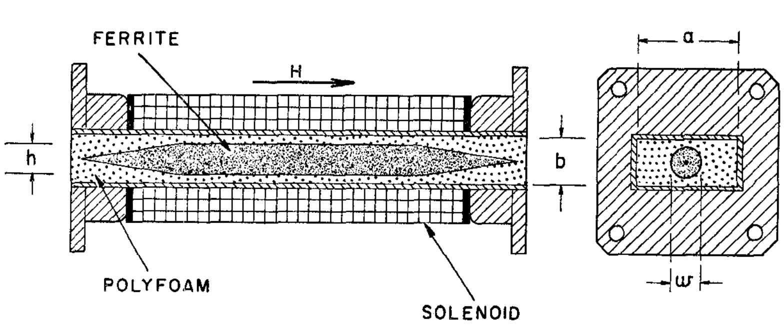
At the left, a side view of the amplitude modulator shows the splitting of the ferrite rod along its length and the thin resistive film (0.0002-inch thick) placed between the sections of this split rod. Note the similarity of this absorption modulator-switch with the phase modulator shown in Fig. 1.

The attenuation characteristics from 4900 to 5600 Mc/s of a broadband amplitude modulator-switch vs. applied magnetic field is shown in Fig. 5. This is a difficult frequency range because good ferrite materials for wide-band operation are not readily available at these frequencies. In spite of this, maximum attenuation values as great as 60 dB, and insertion losses as low as 0.5 dB have been obtained in this frequency range with a 6-inch long MgMn ferrite[2] rod in a standard 1- by 2-inch waveguide. The resistivity of the metallized-mica attenuator element used between the split sections of the ferrite rod was 30 ohms per square. Nearly zero phase shift was obtained with this ferrite rod (height = 0.520 inch, width = 0.560 inch) at 5200 Mc/s. The input VSWR of this modulator remained below 1.2 for all values of the applied field. The solenoid current required to obtain the necessary magnetic field strength is shown at the top of the figure.

The phase-shift and attenuation characteristics from 4900 to 5600 Mc/s of the absorption modulator-switch making use of a slightly smaller ferrite rod ($h = 0.500$ inch, $w = 0.540$ inch) are shown in Fig. 6. Increasing attenuation is plotted along the abscissa, phase shift along the ordinate, and the magnitude of the applied magnetic field increases from left to right along each of the phase-shift curves. As seen in this figure, for a particular ferrite rod and attenuator resistivity, a frequency can be found for which positive, negative, or nearly zero phase shift can be obtained. For this particular case, nearly zero phase shift occurs at 5300 Mc/s. The length and width of the attenuator element (0.0002-inch thick) were the same as those of the ferrite rod. Attenuation values greater than 60 dB were obtained in this frequency range. The insertion loss for this particular ferrite rod (6 inches long) and attenuator element (35 ohms per square) was less than 0.5 dB.

[1] Trans-Tech TT1-105 Al-substituted MgMn ferrite.

[2] Ferramic R-5 MgMn (Al-substituted) ferrite, General Ceramic Corporation.



(a) (b)

Fig. 1. Reciprocal ferrite phase modulator. (a) Side view. (b) End view.

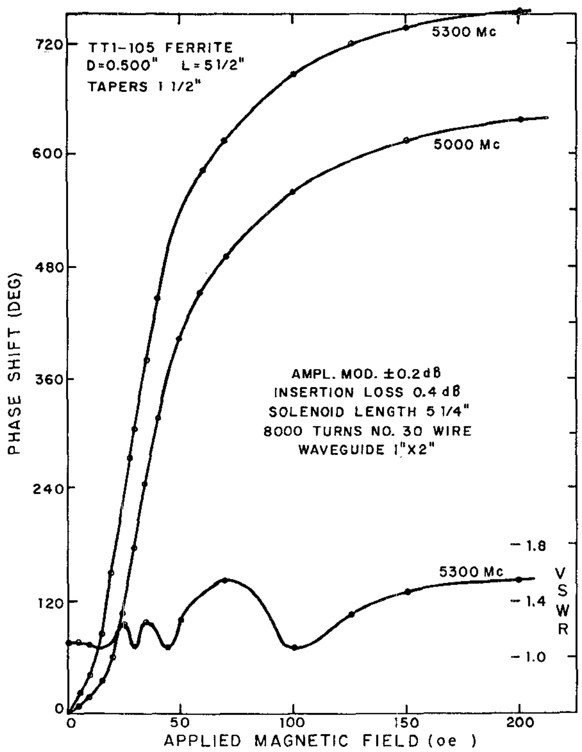


Fig. 2. Phase shift and VSWR of phase modulator.

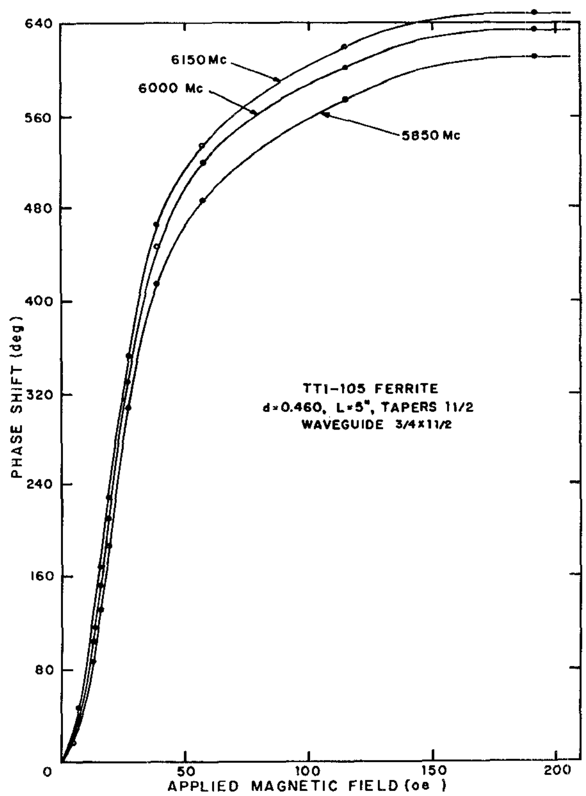


Fig. 3. Bandwidth characteristics of phase modulators.

The phase-shift-attenuation characteristics at 5100 and 5300 Mc/s of the modulator-switch, using the same ferrite rod described in Fig. 6, are shown in Fig. 7 for several values of attenuator resistivity. Beginning with the results obtained at 5300 Mc/s (shown by the dashed curves), a positive phase shift (or phase lead) is obtained with an attenuator resistivity of 20 ohms per square, nearly zero phase shift with a 35-ohm attenuator element, and negative phase shift (similar to that obtained with the reciprocal phase modulator) for a resistivity of 50 ohms per square. Similar results (shown by the solid curves) were obtained at 5100 Mc/s. At this lower frequency, an attenuator element resistivity of approximately 60 ohms per square would be needed to get nearly zero phase shift. Thus, it is seen that there are at least two parameters that can be adjusted to obtain the kind of phase shift desired with the amplitude modulator. The length and width of the attenuator element with respect to that of the ferrite rod can also be adjusted to get similar results.

Finally, the attenuation characteristics over the frequency range from 5600 to 6800 Mc/s of the modulator-switch making use of a new ferrite material[3] vs. applied magnetic field is shown in Fig. 8. The rectangular waveguide used for this frequency range was $\frac{3}{4}$ by $1\frac{1}{2}$ inches, and the total length of the ferrite rod (including $1\frac{1}{4}$-inch linear tapers at both ends) was $5\frac{5}{8}$ inches. The cross-sectional dimensions of this rod were slightly less than those of the preceding rods, being 0.470 inch high and 0.500 inch wide. The attenuator element (0.0002-inch thick) having the same length and width as that of the ferrite rod was a metallized Mylar material with a resistivity of 65 ohms per square.

Similar results, given by Reggia [8], were obtained for the absorption modulator-switch at higher waveguide frequencies to 25 Gc/s. A maximum-to-minimum attenuation ratio of greater than 100 is not difficult to obtain over this frequency range.

A photograph of the phase and amplitude modulators described above for the 5 to 7 Gc/s frequency range is shown in Fig. 9. The same waveguide-solenoid assembly, seen in the background, is used for either the reciprocal phase modulator or the absorption modultor-switch. It is necessary only to change the ferrite-teflon insert to obtain the desired modulator function. In both cases, the same magnetic field strength is required. The low-current solenoid wound around the rectangular waveguide section is plotted in an Epon resin.

[3] Ferrotec P360-62-208 Al-substituted MgMn ferrite.

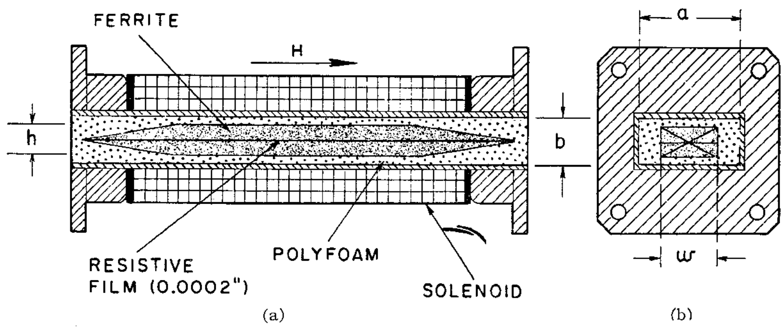


Fig. 4. Broadband absorption modulator-switch. (a) Side view. (b) End view.

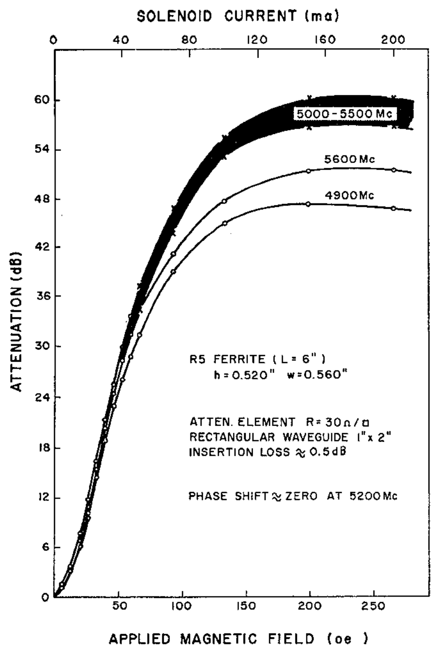


Fig. 5. Attenuation and bandwidth characteristics of modulator.

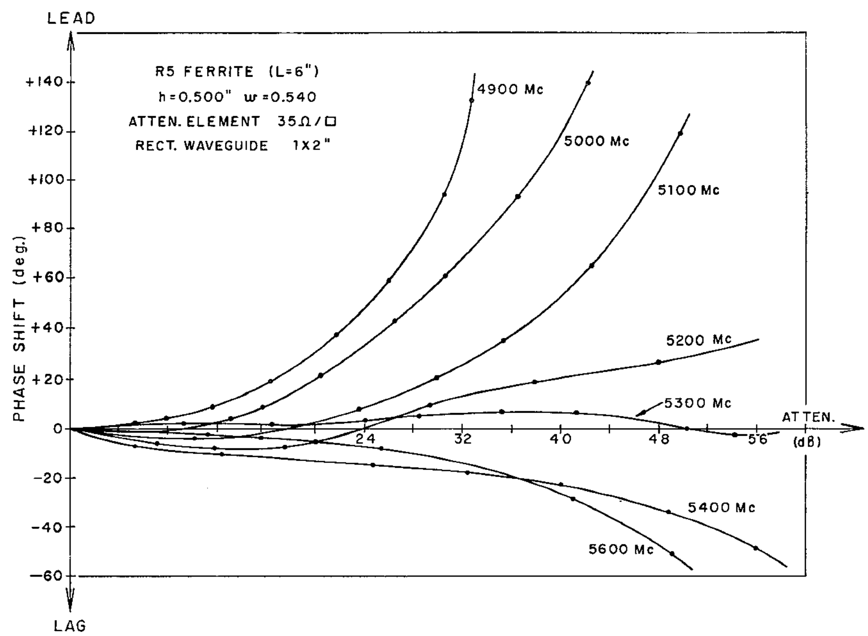


Fig. 6. Phase-shift and attenuation characteristics.

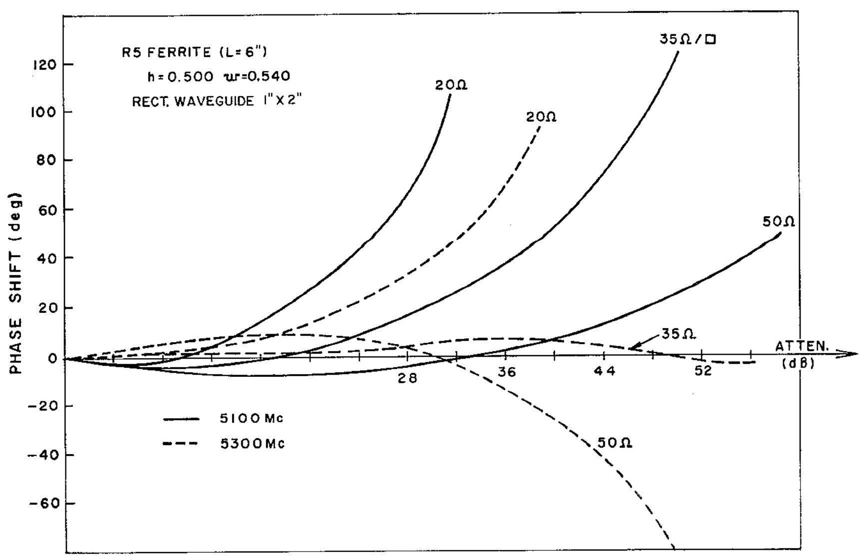


Fig. 7. Phase-shift characteristics of amplitude modulation.

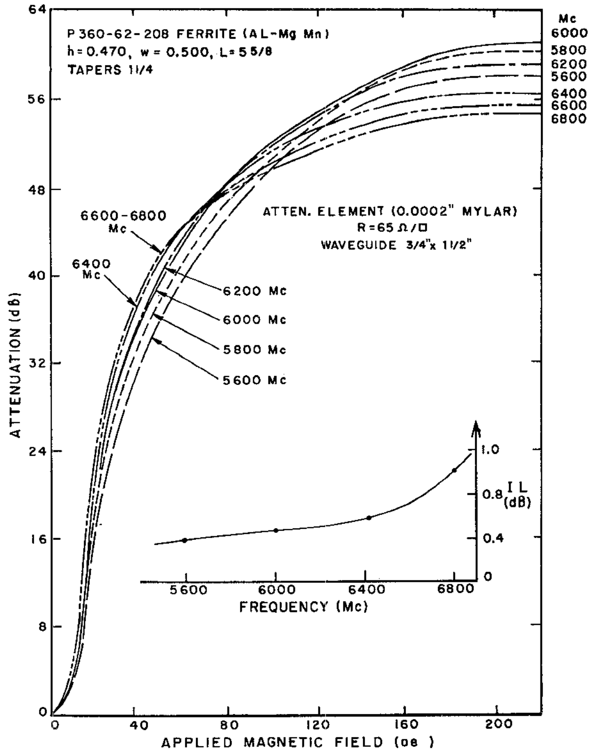


Fig. 8. Attenuation characteristics of amplitude modulation.

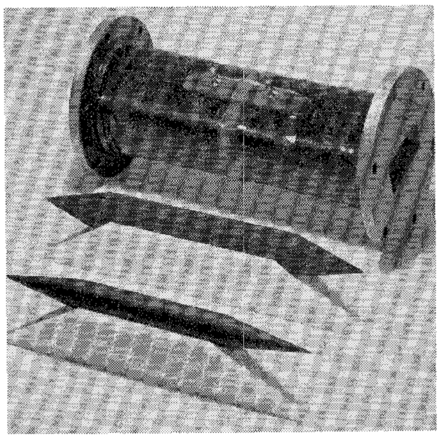


Fig. 9. Reciprocal phase shifters and amplitude modulation.

Conclusion

The reciprocal ferrite modulators described have important applications in microwave systems for antenna beam scanning, amplitude and/or phase modulation, power switching, pulse shaping, and simulating radar target cross section.

An extension of the preceding modulator techniques is presently being used to design a new type of digital (or latching) reciprocal phase shifter for use in phased array antenna systems. These new devices make use of the square loop magnetic properties of toroidal shaped ferrite materials in waveguides. Digital increments of reciprocal phase shift are obtained by latching or switching the ferrite magnetization from a near-zero value to one of its remanent field values.

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Suggested Name "Nanowave Region" for the E-M Spectrum Between 10 Micrometers to 10 Millimeters Wavelength

With the growing activity making use of that portion of the electromagnetic spectrum which lies between the visible and microwave, I would like to enter a plea for an improvement in nomenclature before too many more grotesque synonyms become generally accepted. This is a highly controversial subject, I grant, but one which should be given the dignity of serious discussion by the people who are inventing the jargon.

The activity in this spectral region is a natural extension of the exploratory research and development by microwave engineers and optical engineers. The former bring with them the techniques of radio engineering based upon coherent radiation of long wavelength while the latter bring with them optical techniques evolved from a hundred years of experience with incoherent radiation of very short wavelength. This is bound to produce a provocative technical confrontation completely apart from the semantic confusion of using identical words with different technical definitions, e.g., coherent. Fig. 1 shows some of the spectrum designations commonly and imprecisely used by these two technologies. It does not show other phrases like "far far infrared," "ultra microwave," or "extra high frequency."

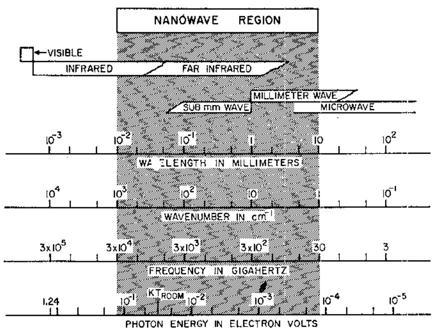

Fig. 1. Electromagnetic spectrum designations.

I propose that the spectrum from 10 micrometers to 10 millimeters be called the "nanowave region" in the same spirit with which the word *microwave* is now used. There are two intended meanings for which I find *microwave* being used: the comparative, in which the Greek prefix mikros (meaning small) is intended and means that component dimensions are of the order of λ, and the definite meaning in which λ is regarded as being of the order of a decimeter. Now *microwave* is an uncomfortable hybrid of two languages, but *nanowave* is not less comfortable, using the Greek prefix *nanos*, (meaning "dwarf"). The analogous double meaning for *nanowave* would be that the dimensions of the components are very large compared with λ or that λ is of the order of a millimeter.

When the word *optical* is examined, it appears that its original Greek meaning,

Manuscript received August 5, 1965.