RADIO ENGINEERING
MICROWAVE RADIO
WAVEGUIDE SYSTEMS
GENERAL THEORY

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1. GENERAL

1.01 This section discusses the basic theory of waveguide systems and devices as applied to microwave radio transmission systems. It provides condensed general information of interest to transmission and maintenance engineers concerned with applications of waveguides but avoids detailed technical theory and extensive mathematical treatment.

2. BASIC THEORY

A. Physical Concepts

2.01 In a broad sense any surface or interface between two regions of significantly different dielectric characteristics will exert a guiding influence on electromagnetic waves. At frequencies below the microwave region, roughly less than 2 gigahertz, the most practical arrangement for transmitting or "guiding" such waves is by discrete wire conductors. These may be twisted or parallel pairs, either shielded or unshielded, or by coaxial cable. The choice will depend on the type of signals, frequencies, bandwidth of interest, and the physical and electrical environment within which it must operate.

2.02 By common usage the term ***waveguide*** as applied to microwave systems means a hollow metal tube or pipe. It is usually rigid; a rectangular, square, elliptical, or circular internal cross section, but flexible types or other shapes may be used for special applications. Electromagnetic power passes through the space inside the guide as electric and magnetic fields. Some electron current flow occurs in the low resistance inner wall but this is incidental to the primary function of the guide and represents an undesired but unavoidable power loss. Figure 1 shows the approximate loss-frequency characteristics of coaxial cable and waveguide of comparable dimensions. The superiority of the waveguide at frequencies above 2 or 3 gigahertz and for relatively wide bandwidths, eg, 3 to 12 gigahertz, is obvious.

2.03 Waveguide is used most commonly as a transmission medium for connecting antenna systems to their associated radio transmitters and receivers. The advantage of low loss is most pronounced on long runs, such as between tower-mounted antennas and equipment located at or near the base of the tower, where the total distance may be up to several hundred feet. But as with coaxial cable, short lengths may often be used as resonant traps, filters, or other circuit components. As the guide is inherently a low-loss device, very high values of Q can be obtained, and efficient filters, couplers, combiners, and other types of networks may be constructed. Such devices are ordinarily used within the radio equipment, or for interconnecting equipment units, or separate systems. Typical examples are shown in Fig. 2. When precise control of frequency response is required, one or more fixed and/or adjustable tuning elements, such as metallic posts, rods, or screws are added to provide fine adjustment and control of transmission characteristics.

2.04 Rigid waveguide or waveguide-type components are usually made of aluminum, brass, or

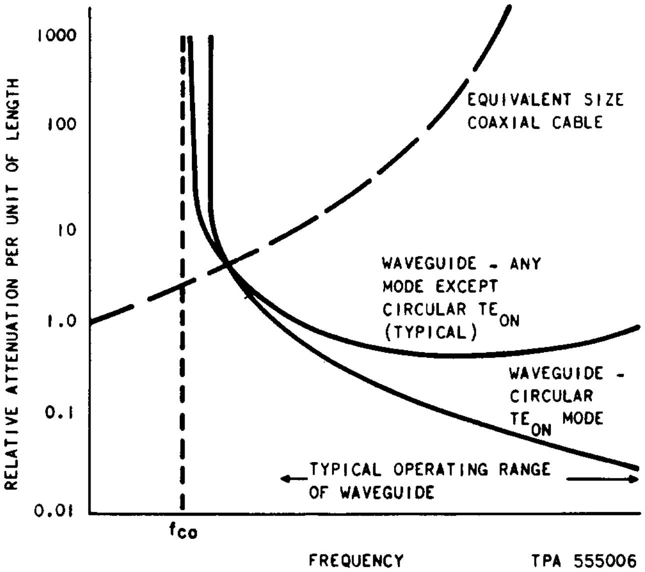

Fig. 1—Relative Attenuation vs Frequency Characteristics of Comparable Size Waveguide and Coaxial Cable

oxygen-free high-conductivity copper with brass or steel flanges on each end. In some cases, components of critical dimensions subject to significant temperature changes may be made of Invar to minimize thermal detuning, and internally plated with silver or other high conductivity metal. Uniform size and shape with smooth inner surfaces is important to avoid impedance irregularities which may cause low return loss and excessive echoes. Flange end-fittings are especially critical since any deviation from perfect mechanical fit between the faces of abutting flanges can allow serious radio frequency leakage into or out of the waveguide. As a practical matter, leakage through a typically tight, properly connected flange joint may have a loss from inside to outside of the waveguide in the order of 85 to 90 dB. But a dented, scratched, or deformed flange surface with defects exceeding 0.5 mil may increase the leakage by as much as 25 dB. Due to the great difference between transmitted and received signal levels at a microwave station leakage of this magnitude may cause intolerable interference.

2.05 In addition to straight sections of waveguide in a wide range of sizes, shapes, and lengths, many other standard components are available. These include bends of 30°, 45°, 60°, 90°, and 180°, in either plane for rectangular shapes, and 90° twists. Transducer sections are available for coupling from one size or shape to another. Some waveguide systems are kept charged with dry air or nitrogen under pressure to prevent the formation of moisture condensate on the inner surfaces. For this purpose short sections of guide are available with a built-in "pressure window". This is a dielectric, gas-tight seal, which will pass microwaves with negligible attenuation. Each "window" unit is fitted with an air valve or port for injecting the air or gas at the bottom end of the pressurized section, and for venting or checking pressure at the distant end, usually just below the antenna.

2.06 Various sizes of flexible guide are available, primarily for connections between the antenna and the guide at the top of the tower, between tower mounted guide and horizontal runs at the bottom of the tower, and from horizontal runs to building entrance fittings, where relative movement may result from thermal expansion or other weather effects. In rectangular guide, transmitting a single band of frequencies of one polarization, flexible sections serve the purpose very well. Their attenuation is higher than the solid guide equivalent, but the flex is usually so short that the added loss is not significant. In multiband systems, particularly those using circular waveguide driving horn-reflector antennas, a flexible section at the tip of the run has inherent nonuniformity plus variations induced by small but finite motion of a flexible section. This produces varying irregularities and unpredictable transmission variations.

2.07 The mathematical principles involved in the theory of electromagnetic wave transmission in waveguide are relatively complex and the related computations can be both difficult and tedious. For transmission and applications engineering, a qualitative understanding with a limited amount of empirical data is adequate.

2.08 More specific quantitative data and greater detail of waveguide theory may be found in various textbooks on the subject.

B. Propagation Modes

2.09 The basic characteristics of wave transmission in waveguides result from the interaction between the electric and magnetic fields inside the guide and the conducting waveguide walls. The electric field lines or vectors at a perfectly conducting

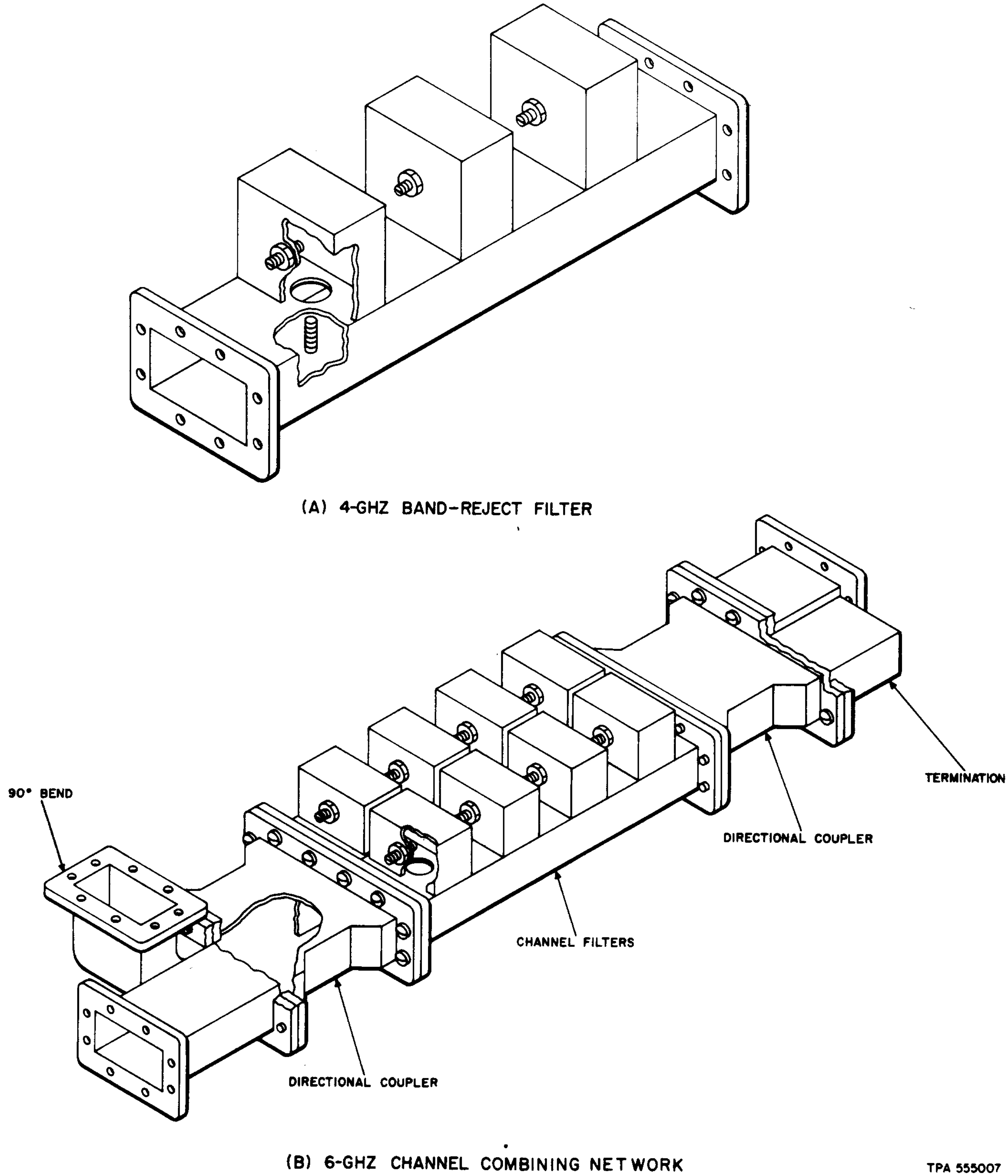

Fig. 2—Examples of Waveguide Type Circuit Components

surface must be perpendicular to and terminate at that surface. The magnetic field or lines of flux always form closed loops, and if adjacent to a perfectly conducting surface must be parallel to that surface. For these considerations the inner surfaces of the guide may be considered perfect conductors, although they always have a small but finite ohmic resistance.

2.10 Two basic types of field configurations are possible within the guide. These are (1) the transverse electric or TE mode in which the electric vectors are everywhere transverse to the guide, and (2) the transverse magnetic or TM mode in which the magnetic vectors or lines are everywhere transverse to the guide. It then follows that a TE mode must have a magnetic field component and a TM mode must have an electric field component, along the axis of the guide.

2.11 To further define the field configuration or mode, the notations TE or TM are usually followed by subscripts m and n, each of which is an integer, as 0, 1, 2, 3.... In rectangular waveguide, m represents the number of half-periods or half-cycles of variation in intensity of the transverse component across the width a, the long side of the guide. Similarly, n represents the number of half-cycle variations of the transverse component across b, the narrow side of the guide. If either m or n is zero, there is no variation of the transverse component across that dimension, ie, across a or b at any given time. To distinguish between rectangular (or square) and circular waveguide a superscript symbol is often used, eg, $TE^{\square}$ or TE°. It may be noted that in a $TE^{\square}$ mode m and n cannot both be zero, and in a $TM^{\square}$ mode ***neither*** m nor n can be zero. Figure 3 shows the field configurations in three planes, for the most commonly used mode, $TE^{\square}_{10}$, and Fig. 4 shows the surface currents and the magnetic field lines which cause them. The surface currents at any given instant flow away from or into centers of the magnetic flux loops. These currents form electric charges of opposite signs at points on opposite sides of the guide. In waveguide systems transmitting very high power, such as some radar systems, internal arcing between high voltage points may occur, establishing a virtual short circuit through the ionized space. In conventional communications systems power levels are seldom high enough to create this problem.

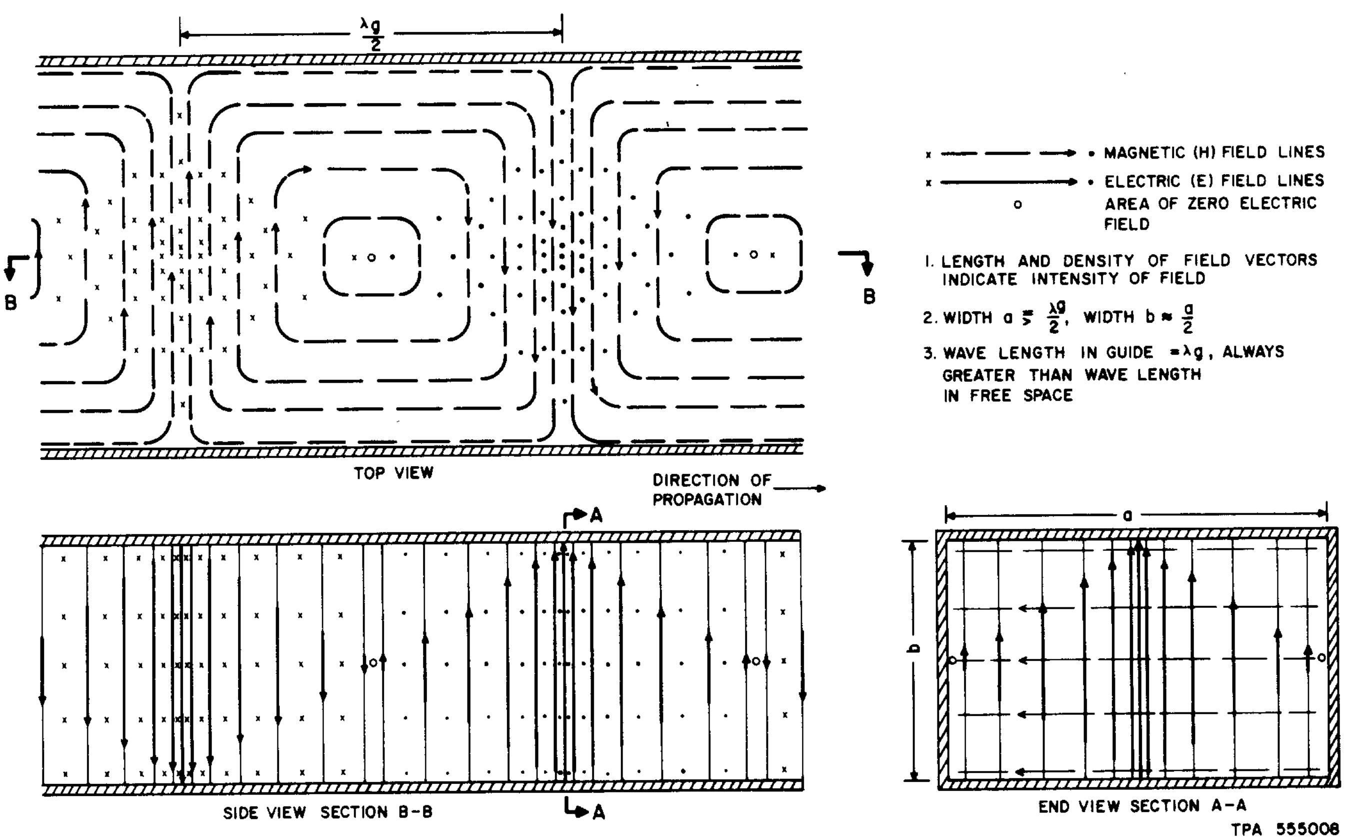

Fig. 3—Relative Fields in Dominant Mode Rectangular Waveguide

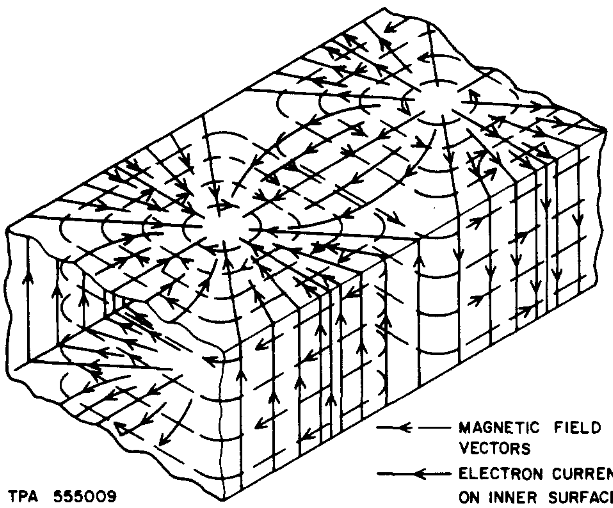

Fig. 4—Surface Current in Rectangular Waveguide

2.12 As indicated in Fig. 1, waveguide has a cutoff frequency, f_{co}, determined by the dimensions of the guide. At or below f_{co} the attenuation and impedance are infinite, and the guide acts like a high-pass filter operated below cutoff. Frequencies slightly above f_{co} will not be transmitted efficiently. In rectangular guide,

$$f_{co(mn)} = \frac{c}{2\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

where $\mu_r = \epsilon_r = 1$ (for air and most gas filled guide)

$c = 3\times10^8$ m/sec (speed of light in vacuum)

a and b are in meters

f_{co} is in hertz

Simplifying,

$$f_{co(mn)} = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2}$$

This indicates that, for a given size waveguide, the lower useful frequencies occur in the lower order modes. As m and n cannot both be zero, and by definition $a \geq b$, the lowest possible frequency will be in the TE_{10} mode. This is the principal or dominant mode; its cutoff frequency $f_{dco} = c/2a$, or for a given f_{dco}, $a = \lambda/2$, when λ is the free space wavelength corresponding to the frequency f_{dco}.

2.13 When a waveguide system is intended to pass a single band of frequencies, significantly less than one octave in width and only one polarization, it is customary to use a rectangular shape having a width, a, greater than one half wavelength and a ratio of b:a equal to or less than 1:2. Such a guide will pass frequencies above f_{dco} and below $2f_{dco}$ only in the dominant mode. This arrangement avoids most of the problems related to multiple-moding and related echo and noise as discussed in Part 4.

2.14 Square waveguide is a special case of rectangular guide in which a = b, and the dominant mode has the same cutoff frequency but can be propagated in either of two polarizations, ie, as $TE^{\square}_{10}$ or $TE^{\square}_{01}$, or two separate signals, one of each polarization can be propagated simultaneously.

2.15 In circular waveguide the mode indicating subscripts must be defined in another way due to the difference in geometry. In this case m represents the number of full-periods or cycles along one complete circumference, and n is related to the field variation along a diameter. (To avoid confusion or misinterpretation it should be noted that some texts and reference books use different definitions for the symbols a, b, m, and n.) In circular guide both TE° and TM° modes are possible; m can be zero in either type mode, but n must be one or greater. The various possible field configurations are similar to those in rectangular or square guide, but distorted or "squeezed" to conform to the circular boundaries. Such similar fields do not have the same subscripts due to the difference in definitions. For example, $TE^{\square}_{10}$ is equivalent to TE°_{11} and each is the dominant mode for that shape of guide. Figure 5 shows examples of some comparable rectangular and circular modes.

2.16 As noted in 2.12, dominant mode rectangular guide must have a width, a, not less than $\lambda/2$ for the lowest frequency to be passed. In the corresponding circular mode, TE°_{11}, the diameter of the guide must be not less than 1.17 $\lambda/2$. For a given dominant mode cutoff frequency f_{dco}, circular guide has a lower loss than its rectangular counterpart for all frequencies above f_{dco}.

2.17 TE°_{0n} modes are particularly unique in that the attenuation is very low, and it ***decreases***

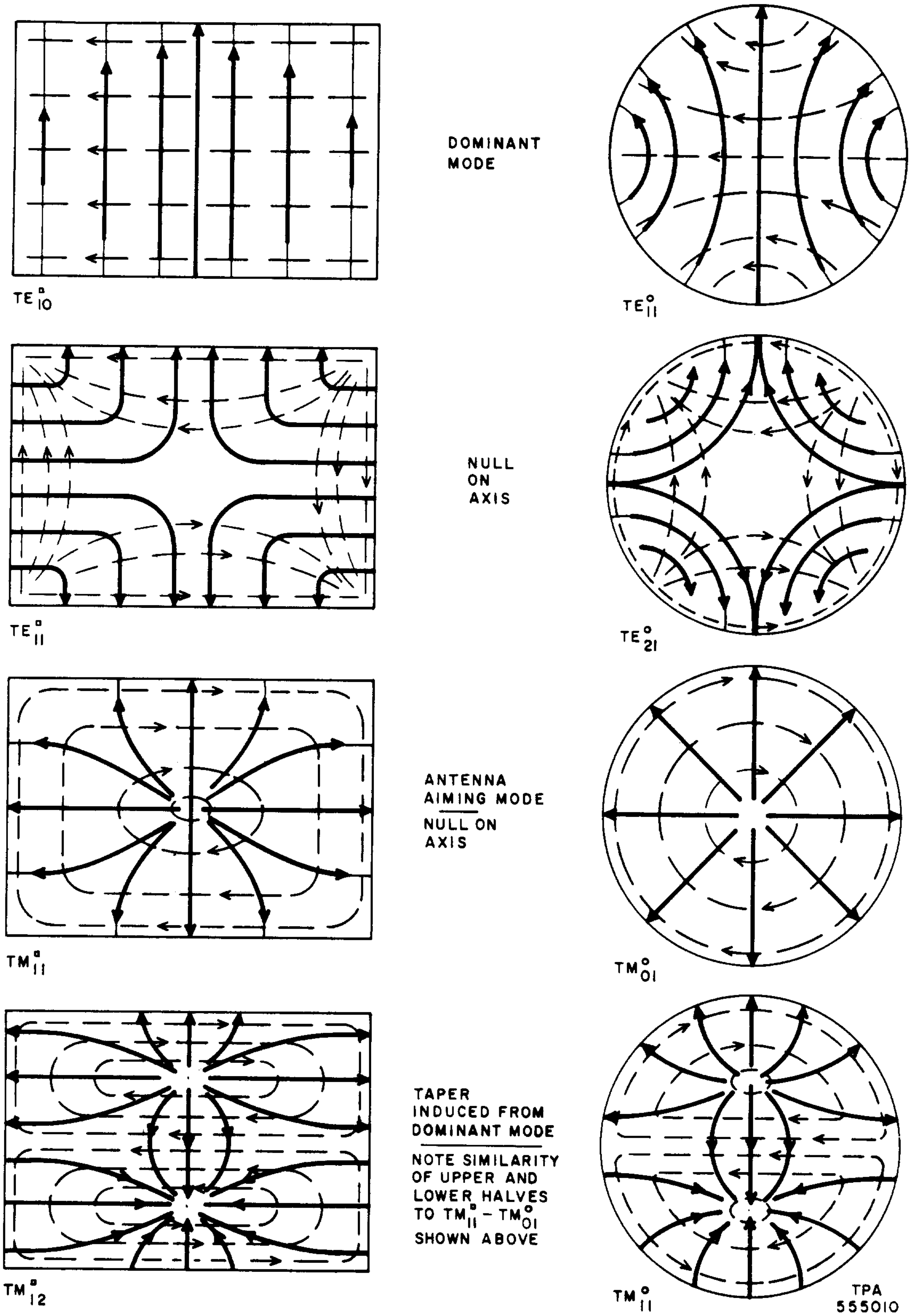

Fig. 5—Comparable Rectangular (or Square) and Circular Modes

indefinitely as the frequency increases. This results from the fact that in any TE^{O}_{0n} mode, as illustrated in Fig. 6, none of the transverse component and a relatively small part of the longitudinal component of the magnetic field is adjacent to the waveguide wall where a current can be induced into the resistive surface. With increasing frequency (or decreasing wavelength) the portion of magnetic field along the surface becomes a smaller part of the total field, so the current and resulting I^2R loss gets smaller. In addition, the currents in the guide surface form closed loops, and there is no accumulation of electric charge on the guide walls as in other modes. This unusual loss characteristic of the TE^{O}_{0n} mode is seldom used to advantage, because it has a higher f_{co} than the dominant TE^{O}_{11} mode and requires a larger size guide for a given low frequency signal.

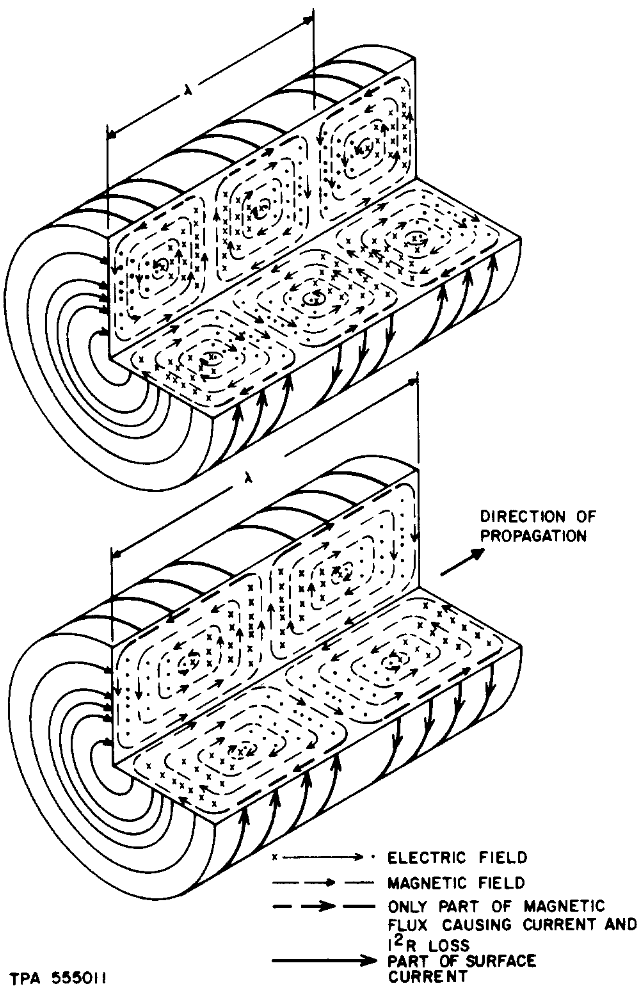

Fig. 6—Modes Showing Field Configurations and Loss-Producing Surface Currents

2.18 A disadvantage of circular guide is its sensitivity to minor physical imperfections, such as those resulting from careless installation or damage in shipping and handling. When used for more than one frequency band with both vertical and horizontal polarization, solid-type circular guide must be perfectly straight or have only very slight bends, generally having a radius of curvature greater than 500 feet. Faulty or misaligned flange joints, small pieces of solder or other foreign matter inside the guide, small dents, slight ellipticity or other imperfections in the inner surface may cause reflections, a shift of polarization, or conversion of some signal energy from one mode to another. These distortions, particularly multimoding, may result in envelope delay distortion and echoes which will appear as intermodulation noise in the baseband signals. Similar effects are produced by other discontinuities, such as waveguide bends, sections of flexible guide, directional couplers, transducers, and terminating devices.

3. WAVEGUIDE COUPLING

3.01 Signal coupling between waveguide and receiver or transmitter circuits is usually provided by a transducer consisting of a wire probe or loop projecting into the waveguide from a coaxial cable fitting mounted in one wall of the guide as shown in Fig. 7. The exact location and size of the probe or loop is determined by the frequency, mode, and polarization of the associated signal in the waveguide. In most microwave transmitters and receivers the transducer is physically a part of the radio equipment assembly, and connection to the external waveguide system is provided at a suitable flange fitting on the equipment.

3.02 Waveguide probe devices may also be provided at other points, either within the equipment or at selected locations in the external waveguide system, as a means of access to the inside of the guide for radio frequency tests. The principal applications are measurement of signal and noise levels in specific modes for tuning or other adjustments, and the observation of undesired signals for use in aiming antennas or to detect trouble conditions, particularly damage to waveguide, misaligned fittings, or other faults in the antenna and waveguide system.

3.03 Coupling between a waveguide system and free space is provided by a feed horn and antenna reflector system, but for theoretical considerations the antenna system can be considered

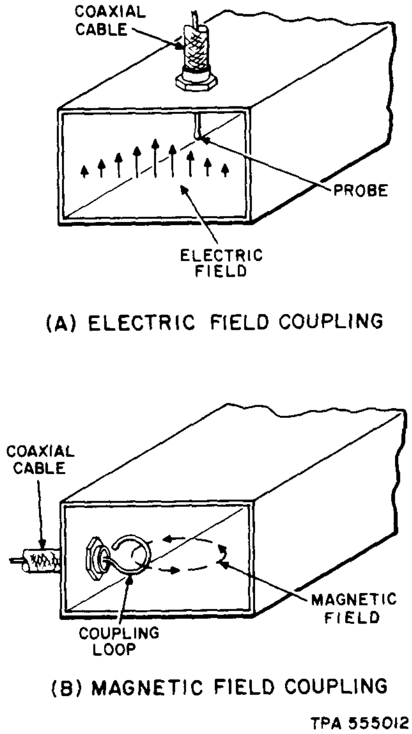

Fig. 7—Coupling Into or Out of Waveguide

as one terminal of the waveguide. Any impedance irregularity in the antenna itself creates a reflection into the waveguide, and may convert part of the signal power to another mode or polarization. Parabolic antennas, as commonly used on short-haul or lightly loaded routes, are usually fed by a separate rectangular or square waveguide for each frequency band used. The antenna end of each waveguide has a flared or small horn section, usually pyramidal in shape, to provide a smooth transition between the guide impedance and the impedance of free space as seen looking from the throat of the horn into the reflecting parabolic surface. This arrangement permits each waveguide to operate at its dominant mode, and the problems associated with multimoding and echoes seldom cause any significant degradation of the signals.

4. ECHO PHENOMENA

4.01 In typical single band systems or short-haul wideband systems parabolic antennas are commonly used, with each radio frequency band fed through a separate dominant mode rectangular waveguide. Each waveguide is small enough so that only the principal or dominant mode can be transmitted. In such a system echoes in the waveguide are caused by mismatches to the dominant modes, and these are primarily at the ends of the waveguide as shown in Fig. 8. For this type of echo, control of the return loss of the individual components in the antenna system will result in adequately low echo levels, typically 50 to 60 dB below the primary signal level.

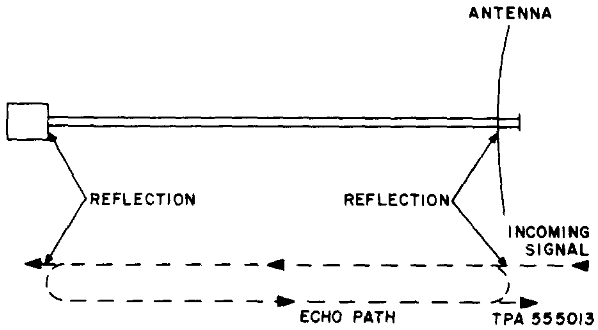

Fig. 8—Dominant Mode Echo

4.02 The general case for echo generation and analysis is shown in Fig. 9. An echo can occur in any transmission system if a path exists by which a part of the original signal can arrive at the receiver displaced in time from the primary signal. Consider a desired signal with an amplitude of 1, and a delayed signal of amplitude, r, displaced in time by, T, seconds. The approximate transmission characteristics are:

Resultant amplitude $\approx 1 + r \cos (T\omega)$

Phase ϕ (in radians) $\approx r \sin (T\omega)$

Envelope delay (in seconds) $= \dfrac{d\phi}{d\omega} \approx r\,T \cos (T\omega)$

Where ω is radian frequency

This shows up as a ripple on an envelope delay or amplitude trace, which repeats every $S = 1/T$ hertz. S is called the ripple spacing. For the transmission of FM signals the phase term of the transmission characteristic leads to a disturbance of the complex phase interrelationships of the signal, and in a system carrying frequency multiplexed telephone channels these disturbances produce intermodulation noise in the baseband signal. Figure 10 indicates the magnitude of such noise in some typical systems as a function of the ripple

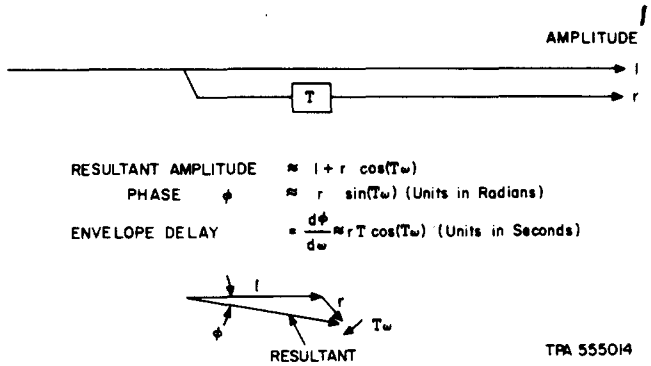

Fig. 9—Approximate Delay Characteristic

spacing for an assumed 40-dB echo. For other echo levels the noise varies dB for dB with echo amplitude.

4.03 Part of a signal radiated from a transmitting antenna may encounter a reflective obstacle close to the direct signal path in space or on a minor lobe of the antenna radiation pattern. A part of the original signal can then travel from transmitting antenna to reflector, to receiving antenna, arriving later than the direct signal due to the greater distance traveled. A close-in obstacle can cause significant reflection back into a transmitting antenna, where a second reflection will restore a part of the energy to its normal desired path, but delayed by twice the travel time between the obstacle and the antenna. Reflections from obstacles may be altered in polarization, further complicating their contribution of objectionable products to the normally received signals. While such phenomena do not alter the theoretical considerations of the waveguide system itself, they are mentioned here because the end result cannot readily be distinguished from echoes induced by the waveguide components.

4.04 While echoes in dominant-mode systems are generated by return-loss reflections, most of the objectionable echoes in horn-reflector antenna systems are caused by higher-order modes that can be propagated in the wideband circular waveguide generally used. These modes are unable to enter the rectangular waveguide to the intended radio equipment and are almost totally reflected by the transitions in the combining network at the bottom of the vertical waveguide.

4.05 Engineering of waveguide installations for application in Bell System microwave systems is covered in Section 940-340-131, and corresponding information on combining networks in Section 940-340-132.

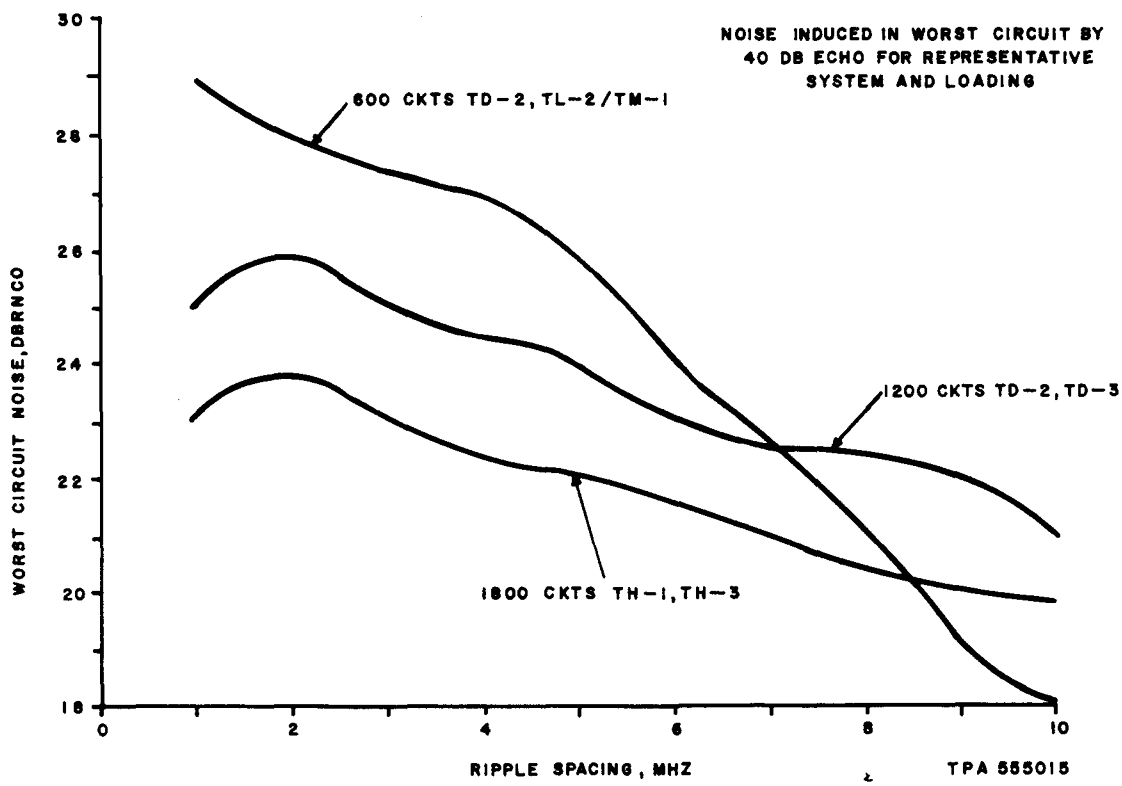

Fig. 10—Noise Induced in Worst Circuit by 40-dB Echo for Representative System and Loading