TRANSMISSION MEDIA FOR MILLIMETER-WAVE INTEGRATED CIRCUITS

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ABSTRACT

A description and comparative evaluation is presented of the characteristics of major transmission means from a viewpoint of their usefulness in integrated planar circuitry for millimeter waves in the frequency range of 30 to 300 GHz.

Introduction

In a great variety of military and civilian applications, the use of millimeter waves with frequencies in the range of 30 to 300 GHz is advantageous. Table I shows a list of such applications. Low interference, narrow beamwidth, increased bandwidth, large Doppler shift, low probability of intercept, and compactness of components and circuitry are favorable characteristics. The properties of sources in the form of tubes and solid-state devices and those of mixers and receivers are continuously being improved and are no longer in the category of disadvantages.

Disadvantages however, exist also. Clear-air attenuation is moderate at frequencies in the valleys of the absorption spectrum. Losses in fog and light rain are moderate also. They are smaller, however, than those of optical waves and infrared. In some applications (low probability of intercept), attenuation such as that at the peaks of the absorption bands actually becomes an asset.

Rectangular waveguides and passive components using rectangular guides are commercially available and cover the whole frequency range up to 325 GHz. As a transmission medium for low-cost integrated circuitry, rectangular waveguides are not practical. Circuitry based on rectangular waveguides is complicated, is difficult to fabricate, and is very expensive. It is not suitable for large-volume applications.

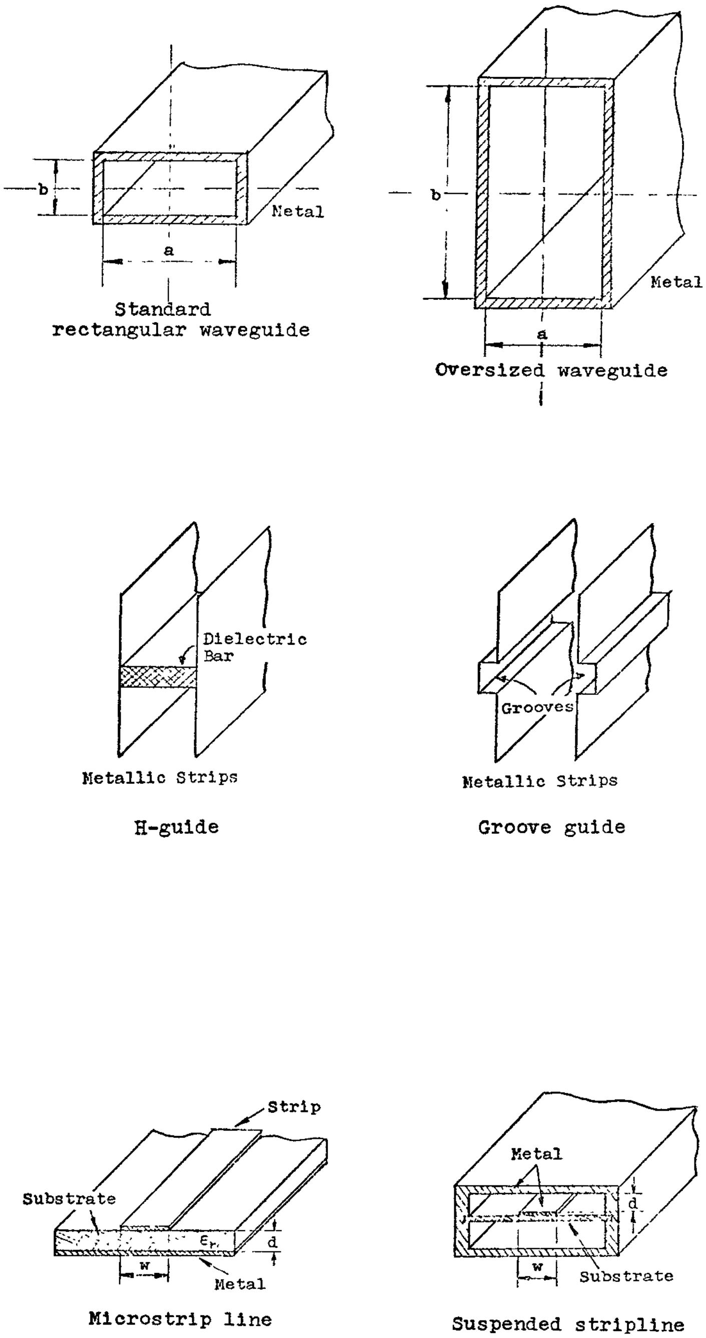
There exists a variety of other transmission media also. Several of them are at present used as the basis of developing components and systems. But the situation is rather confusing. Although specialized devices and components are frequently described in the electronics literature, no comprehensive listing and description can be found. A comparative evaluation of the major transmission media was never published. It is the purpose of this paper to present a list and description of the major transmission media and their characteristics.

Available Transmission Media

The present situation in developing technology for the frequency range of millimeter-waves is not unlike that in the 1940's when microwaves were under development. A major difference exists however: just two major competitive transmission media existed at that time for microwave use - coaxial transmission lines and rectangular waveguides. Today we have a whole array of different structures available for the use in millimeterwave circuitry. On the following pages, figures of the cross sections of the various media will be shown on the left and descriptions and indications of the characteristics will be presented on the right-hand side.

TABLE I
PRINCIPAL CLASSES OF APPLICATIONS

APPLICATION	MILITARY	CIVILIAN
COMMUNICATIONS	Fixed Station-to-Station Ship-to-Ship Communicator Ship-to-Ship Via Drone Ship-to-Satellite Link Satellite-to-Satellite "Secure:, LPI" (low probability of intercept)	High-Capacity Trunk Lines Short-Distance (high-capacity) Computer-to-Computer Link Satellite Communications
RADAR	High-Resolution Radars Search and Track Radars Range Finders Active Fuses Active Missile Seekers LPI Radars Target Designators	Velocity, Distance, Acceleration in Railway Traffic Anti-Collision of Automobiles Industrial Radars Speed Radars Aid for the Blind
SENSORS AND RADIOMETRY	Terrain Imaging (Seekers) Target Seekers Passive Fuses Classifiers	Astronomy Meteorology Plasma Diagnostics Obstacle Sensors for the Blind
SMALL-SIZE SYSTEMS	Smart Weaponry Terminal Guidance of Rockets, Bombs, Projectiles Hand-Held Radars Hand-Held Communicators	Hand-Held Communicators Ambulant Communication Links Hand-Held Sensors for the Blind
AUGMENTATION SYSTEMS	Terminal Guidance Beam Riders Imaging	
ELECTRONIC COUNTERMEASURES	Electronic Countermeasures	Speed Radar Detectors



a. Standard Rectangular Waveguide.[1] The characteristics of these waveguides are well known. Drawn sections of waveguides are difficult to manufacture, they usually do not meet specifications, have considerable losses, and are expensive. They are considered unsuitable for mass-produced circuitry.

b. Oversized Rectangular Waveguide.[2,3] Increasing the height leads to an oversized waveguide and causes a reduction of the attenuation. Higher order modes may be excited. The structure allows incorporation of dielectric elements and offers possibilities for design of quasi-optical circuitry. New techniques would have to be created to make such structures useful for integrated systems.

Electroforming in combination with new planar design concepts may eliminate some of the difficulties associated with the above two types of waveguides.

c. H-Guide.[4,5] The H-guide is an open waveguide with the cross section of an "H". Surface waves, reflected between the sidewalls, carry the energy along the guide. Energy transport is concentrated in and near the dielectric bar with the fields decreasing exponentially from the dielectric toward the upper and lower openings. The attenuation is low, similar to that of the oversized rectangular guide. Excitation of higher-order modes, however, is drastically reduced by the dielectric bar.

d. Groove Guide.[6,7] The groove guide belongs into the group of H-guide structures and has similar properties. The longitudinal grooves in the sidewalls cause a surface-wave type field configuration in the regions above and below the grooves. Elimination of the dielectric bar reduces the losses, and the attenuation is similar to that of the oversized rectangular guide. Excitation of higher order modes is reduced.

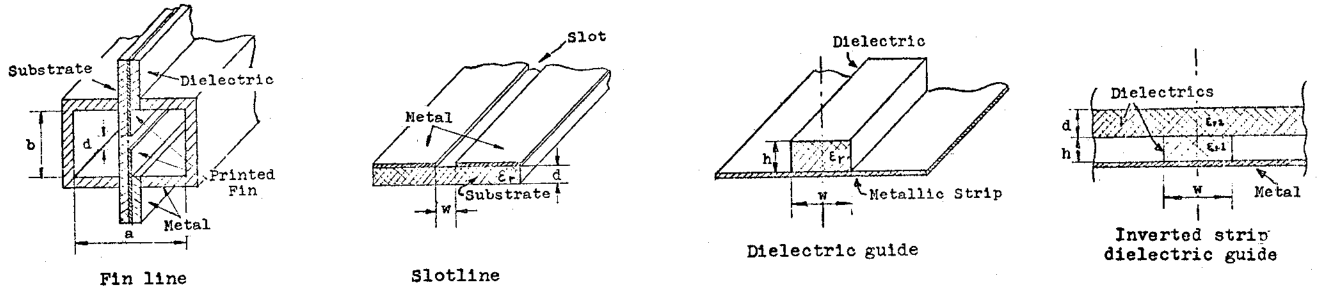
Both, H-guide and groove guide were objects of a Swedish patent application by the author in 1952. H-guide structures will be described later in greater detail.

e. Microstrip Line.[9] In the low-frequency range of millimeter waves, striplines are considered suitable guiding media for millimeter-wave integrated circuits. Their usefulness, however, has an upper-frequency limit. It is given by high losses, excitation of leaky surface waves traveling along the dielectric away from the strip, seemingly difficult tolerance problems, and radiation by bends and discontinuities.

f. Suspended Stripline.[10] The suspended stripline is a somewhat improved form of the stripline. Reduced thickness of the dielectric substrate decreases the losses and shielding eliminates transverse coupling and radiation. Breakage of the substrate is a possibility in the case of some materials.

Extensive manufacturing facilities are probably necessary to fabricate stripline-type integrated circuitry. Whether large production demands exist to justify such efforts is uncertain at present.

Fig. 1. Most common millimeter waveguides suitable for integrated circuits.



g. Fin-Line.[11] Components based on the fin-line are at present under development. The structure is a slotline enclosed by a shield similar to a rectangular waveguide. It actually has the form of a ridged rectangular waveguide with the ridges isolated by dielectric slabs. This, in a way, defies the purpose of shielding since waves travel in the dielectric out of the guide. The structure allows simple design of the actual slotline elements but, in combination with the shield, fabrication does not seem less complicated than of components based on rectangular waveguides.

h. Slotline.[12] Slotline and stripline are often assumed to be complementary. This is not exactly true since there exists no longitudinal path of conduction currents in the slotline which would support quasi TEM waves as is the case on striplines. Planar circuitry can be designed with this guide but transverse confinement of the fields is unsatisfactory.

The attenuation of slotline and fin-line is high and the Q-factors low. Incorporation of solid-state devices, however, is simple.

i. Dielectric Guide.[13] The structure is often called "image line" since, in the absence of the conducting surface below, it represents the upper half of a dielectric guide of twice the height. It has a few disadvantages. If the losses are to be low, the fields reach far out into the surroundings; if the fields are well confined, the dielectric losses are high in addition to the considerable losses in the conducting image surface.

k. Inverted Strip Dielectric Guide.[14] The improvements resulting from adding a dielectric sheet on top of the image line are not sufficient to eliminate drastically the disadvantages associated with the field configuration of the image line.

In both lines, bends and discontinuities cause excess radiation. Incorporation of solid-state devices is problematic.

H-Guide Structures

In consideration of the H-guide, one usually thinks about a single type of guiding structure. This, however, is far from the facts since the H-guide concept involves a whole family of waveguides with different cross sections. Figure 2 shows the major configurations which belong into this group of guides. They are basically characterized by confinement of the fields sideways by conducting walls* or wire grids (fence guide) and vertically by surface-wave propagation with the fields decreasing exponentially toward the upper and lower openings. If upper and lower walls are provided, the basic field configuration is not appreciably altered.

Basically, the guides in this category avoid many of the disadvantages which other guides, such as the image line, have. They represent optimized electromagnetic structures. Some of them are extremely well suited for the design of integrated circuits for low-cost massproduction.

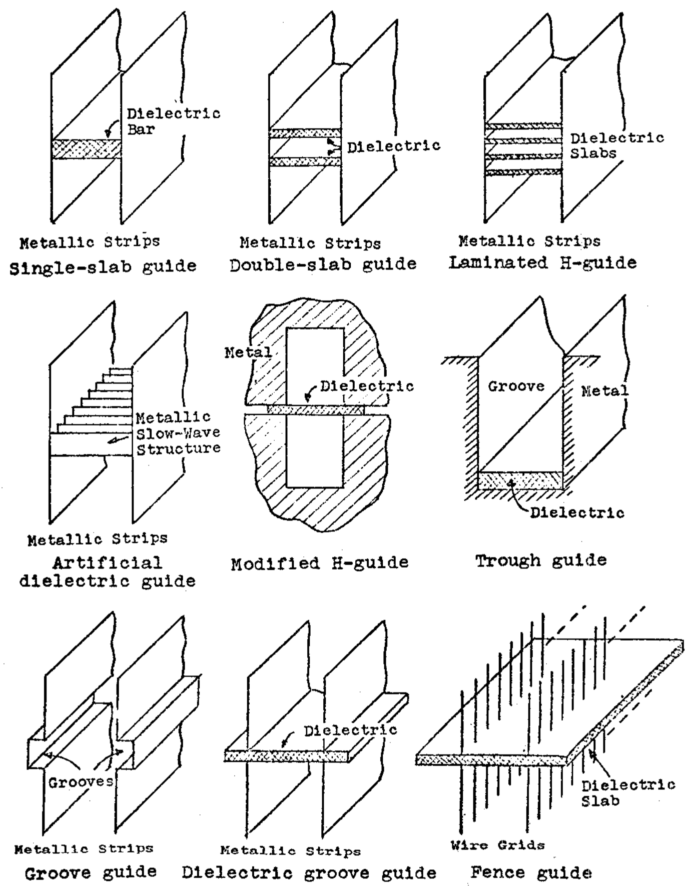


Fig. 2. H-guide structures.

*It is interesting to note that for the low loss mode the contribution to the attenuation by the sidewalls is practically negligible.

Fence Guide

The fence guide[8] shown in Fig. 2 in the lower right-hand corner is the most recently developed modified H-guide. Its sidewalls consist of wire grids which replace the solid sidewalls of the original H-guide. Since the E-vector of the waves propagating between the grids is parallel to the wires, the wire grids act effectively as reflectors. The field configuration is practically the same as that of the H-guide with the fields decreasing exponentially toward the upper and lower openings. The fields outside the grids are about 40 dB below the field amplitude in the center of the guide. The slab which carries the wire grids can support a complete integrated circuit such as a receiver front end. A design example is illustrated in Fig. 3. A block of foam material may contain the complete circuit.

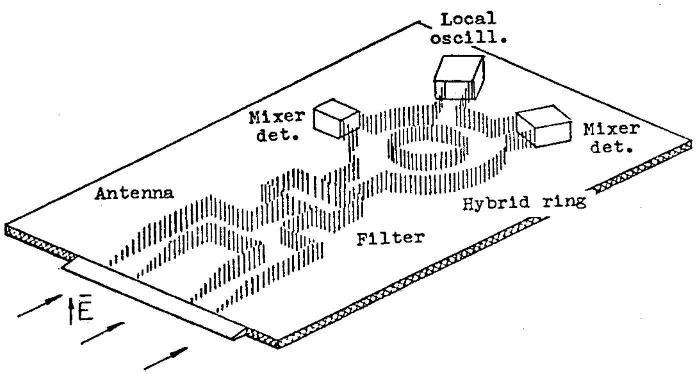


Fig.3. Millimeter-wave receiver made of fence guide.

Models of the fence guide and components were fabricated and experimentally investigated. The experiment showed no unfavorable properties. No excess radiation from the upper and lower openings was observed in bends and ring circuits. The structure seems ideally suited for mass-produced millimeter-wave circuitry.

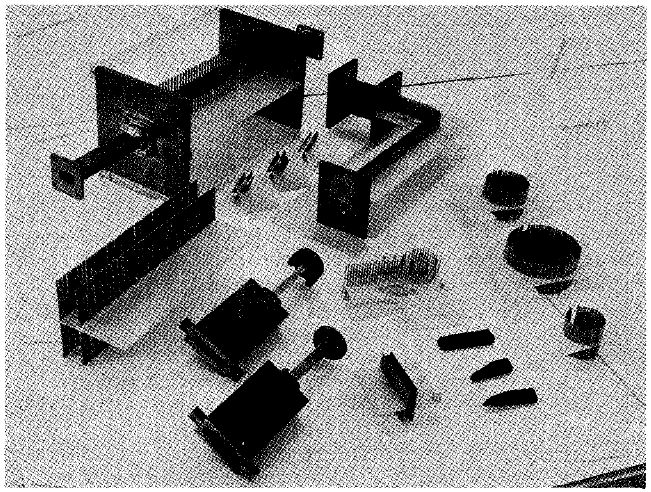


Fig. 4. Fence-guide model (K_u band) and components investigated at 35 GHz. Bends, ring circuits, termination, and attenuator.

TABLE II

COMPARISON OF CHARACTERISTICS OF WAVEGUIDE STRUCTURES

	Cross-Sectional Dimensions	Q-Factor*	Power Rating+	Adding Solid-State Devices+	Potential for Mass-Production°	Leakage (Field Confinement)
Standard Waveguide	moderate	moderate	moderate	moderately difficult	poor	zero
Oversized Waveguide	oversized	high	high	no assessment	poor	zero
H-Guide	oversized	high	high	no assessment	moderately good	small
Groove Guide	oversized	high	high	no assessment	moderately good	small
Fence Guide	oversized	moderate	not known	no assessment	very good	moderate
Microstrip Line	small	low	low	easy	moderately good	moderate
Suspended Stripline	moderate (shielded)	low	low	easy	poor (shielded)	zero (shielded)
Fin-Line	moderate (shielded)	low	low	easy	poor (shielded)	zero (shielded)
Slotline	small	low	low	easy	moderately good	considerable
Dielectric Guide	moderate	moderate	moderate	difficult	moderately good to poor	considerable
Inverted-Strip Diel. Guide	moderate	moderate	moderate	difficult	moderately good to poor	moderate to considerable

*Low = 50 to 500; moderate = 500 to 4k; high=above 4k(40GHz); Q = 1/Attenuation.
+Qualitative statement; relative to rectangular waveguide.
°Anticipated potential.

Frequency Ranges of Waveguide Structures

The frequency ranges for the usefulness of the previously described waveguide structures is shown in Figure 5. The estimate is based on potential production models rather than laboratory models made as a single item.

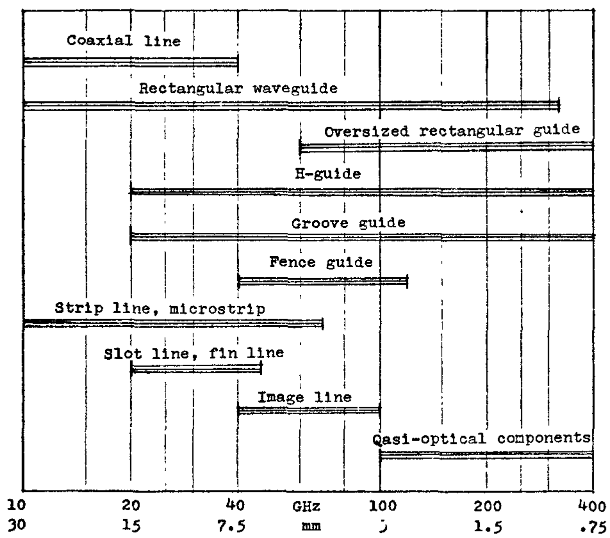


Fig.5. Useful frequency ranges of millimeter waveguides.

Comparison of Characteristics

An attempt to evaluate comparatively the transmission media is shown in Table II. The evaluation has the form of preliminary estimates since there are so many variables involved. Most structures are described and available as laboratory models only, and the characteristics, which in most cases vary with frequency, depend on the future fabrication methods. A frequency of 40 GHz was used as a basis for the comparison. New concepts and approaches may change the estimates. In many cases, technologies to fully utilize the potentials of the structures have yet to be developed.[15]

In conclusion it may be stated that rather determined and very intelligently planned efforts will be required to create a technology as a basis for a potentially abundant market in the future.

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