CERAMIC WAVEGUIDE MICROWAVE INTEGRATED CIRCUITS

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Abstract

The transmission line to be described uses a plated ceramic as the waveguide or coaxial medium and represents a practical circuit integration technique for frequencies from C-band through at least K_A-band. Preliminary investigations indicate that fabrication techniques are commensurate with high level integration and low cost.

Introduction

This paper describes a new microwave transmission line technique that has the potential to offer major technological improvements in microwave integrated circuits for applications at C-band through at least K_A-band and for selected circuits at lower frequencies. This transmission line, referred to as Ceramic Waveguide (CWG) essentially consists of replacing the air dielectric in rectangular, circular and coaxial waveguides with a ceramic or equivalent solid material. The ceramic structure provides both the support for the metal boundaries and is amenable with existing fabrication techniques to the development of low-loss, compact, lightweight, high production integrated active and passive circuits and modules.

The above conviction is supported in the following sections. The first section presents a general comparison of ceramic waveguide with other transmission lines; the second, ceramic waveguide electrical and physical parameters; the third, specific circuits and their characteristics; and finally, the materials and fabrication techniques for low-cost development.

SECTION I

GENERAL COMPARISON WITH OTHER TRANSMISSION LINES

Table 1 compares the major transmission lines at X-band on a merit basis of 1 to 5 where 1 is the highest figure of merit and 5 the lowest. Air rectangular waveguide is the reference. From this Table one could conclude the C.W.G. is a favorable format for integrated circuits at X-band.

SECTION II

ELECTRICAL AND PHYSICAL PARAMETERS

The electrical characteristics of ceramic waveguide can be derived from the usual waveguide formulas for propagation constant. Thus, all of the formulas of standard air waveguide are applicable with corrections defined by the properties of the relative ceramic dielectric constant, ϵ_r, and loss tangent, $\tan\delta$.

The ceramic guide wavelength for low loss ceramics is given by

$$\lambda_g = \frac{\lambda_o}{\sqrt{\epsilon_r - \left(\frac{\lambda_o}{2a}\right)^2}}$$

where a is the ceramic waveguide wide dimension. Essentially both the wavelength and the impedance of ceramic waveguide, if scaled are reduced by the same scaling factor.

The losses in ceramic waveguide will be theoretically greater than in air waveguide for two reasons: the loss due to the dielectric itself, and the increase in current density at the metal dielectric sheath.

The losses measured on X-band alumina waveguide (a = .290", b = .128") with surface finish of 16-25 microinches and sputtered Cr-Au metalization were .05 to .07 dB/in. Theoretical losses are .02 dB/in. for this ceramic and this is to be compared to .0015 in WR-90 and .2 in microstrip.

The power handling of waveguides is proportional to the cross-sectional area, the square root of dielectric constant and dielectric breakdown. Peak and average power handling will be further reduced by the degree of surface roughness. The most limiting factor, is the heating caused by the increased losses over air guide as mentioned previously. Tests have been performed on S-band scaled alumina waveguide with 25 microinch finish; and at peak powers to 15 kW and average power to 1 kW no breakdown conditions existed but the heating was excessive.

Circuit isolation tests have been made on alumina ceramic waveguide and the results show that dependent on plating thickness, isolations approaching standard air waveguide can be achieved.

Only qualitative remarks are in order as to the ultimate mechanical "goodness" of ceramic waveguide (CWG) for integrated circuits. For single circuit designs CWG represents a formidable improvement over microstrip. It is stronger, requires no superstructure, transitions are simply mechanized, plating is contiguous, and devices are readily inserted. Integrated active modules have been fabricated in both ceramic waveguide and microstrip and these same comments apply plus the fact that the CWG module was smaller and weighed approximately 1/3 that of the microstrip module.

One of the major problems of all microwave distributed circuits is the circuit performance as a function of temperature. Two factors affect performance. The first is due to elongation of dimensions with temperature and the second due to the change of dielectric constant. Neglecting loss which is relatively small any filter circuit becomes a potential problem for the designer because of frequency drifts with temperature. For example, the frequency variation as a function of temperature of a CWG filter is given by[1]

$$\frac{1}{f}\frac{df}{dt} = -\left(\frac{I}{2} + \sigma\right)$$

where

$$\sigma = \frac{1}{L}\frac{dL}{dT} = \text{expansion coefficient}$$

[1] C. P. Hartwig, M. P. Lepie, D. Masse, A. Paladino and R. A. Pucel, "Microstrip Technology", Proc. National Electronics Conf. 24, 314 (1968).

and

$$\tau = \frac{1}{\epsilon_r} \frac{d\epsilon_r}{dT} = \text{dielectric temperature coefficient}$$

For alumina waveguide, σ is less than 10 ppm/°C and τ is approximately 150 ppm/°C. A filter must be designed to account for this change or a compensated ceramic should be used. A compensated ceramic requires $1/2\ \tau = -\sigma$ and work on such ceramics has been reported(2).

SECTION III

CIRCUIT DESIGNS

The ceramic waveguide circuits were developed mainly at X-band and included a slotted line, couplers, tapers, loads, transitions and circulators.

A non-radiating, single mode slotted line, after several attempts using etching and grinding techniques, was designed at X-band using a special indexing jig for slot location. In conjunction with this, coax-to-waveguide transitions and waveguide flanges were developed. The former provided a match better than 1.5:1 over the band 7.4 to 12.0 GHz. The flanges were soldered or epoxied to the plated waveguide and then the face was lapped - a perfect interface resulted and no resonances were observed over the X-band.

Loads were constructed several ways but the most successful was to mold the lossy material to the ceramic taper and then metalize. VSWR's of less than 1.1:1 were observed.

For ceramic waveguide designs, circulator impedance matching is considerably simplified since the dielectric constant of the ferrite and ceramic are similar. A preliminary design with a single 1/4 λg step, as in Figure 2, provided a 20 dB isolation bandwidth of 23 percent and .4 dB insertion loss.

Filters have been designed using drilled holes as well as septums. A 6 pole 4 percent bandwidth filter at C-band had .8 dB loss and skirts approaching rectangular guide capability.

Both Gunn and avalanche oscillators in ceramic cavities, coaxial and waveguide, have provided the same power capability as in standard guides. VCO's using varactor tuning have given a minimum 10 percent tuning band. Also, YIG tuning has been realized with Gunn devices.

Another interesting active circuit is the transistor amplifier. A coaxial package with common base is shown in a ceramic circuit in Figure 3. The frequency was circa 4 GHz.

Most of these circuits have been developed from handbook information on coaxial and waveguide circuits. Simple scaling provides the design prescriptions.

SECTION IV

MATERIALS AND FABRICATION TECHNIQUES

Table II summarizes the properties of various ceramics of interest to the microwave engineer. This is a representative list of candidates and is by no means exhaustive. Conventional fabrication techniques such as grinding and lapping are expensive in production and so other techniques have been investigated.

One of these is the so called "green" process in which a bindered ceramic is compressed or formed to the desired shape and then "fired" to final dimensions. A second method is to form the circuit by compression, sinter the form, machine to dimensions - allowing for proper shrinkage - and then final fire. This procedure permits greater latitude in developing more complicated configurations. An example using this technique is shown in Figure 4. Another method which we call the "cookie cutter" technique forms hard-fired alumina by an ultrasonic impact grinder. Nearly all of the planar circuits that have been developed at Raytheon have come this route. An estimate of costs for the circulator was $27 in lots of 100. Other techniques are being investigated which are variations of the above.

Conclusions

The ceramic waveguide technology described offers a highly promising new approach to integrated circuits. One can predict many new and interesting circuits using bulk ferrites diodes and even gas devices.

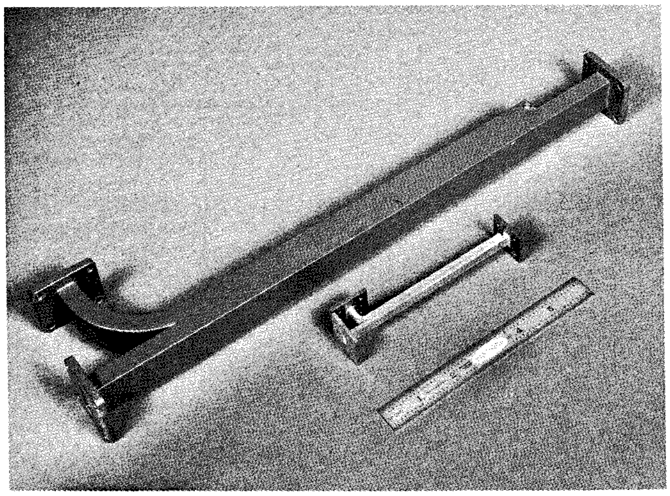

FIG. 1. CERAMIC WAVEGUIDE DIRECTIONAL COUPLER

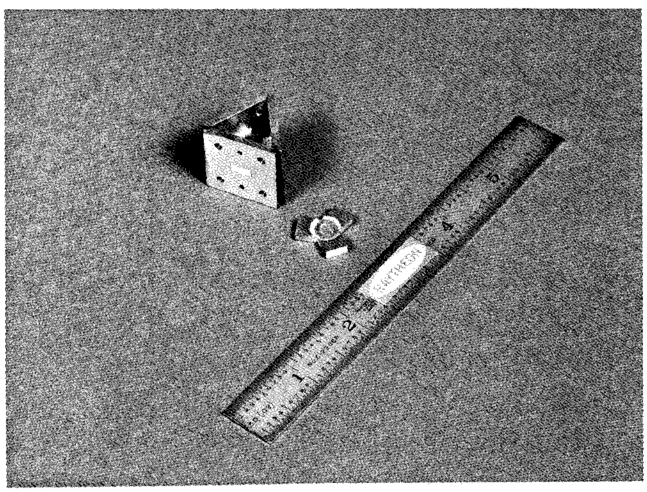

FIG. 2. CERAMIC WAVEGUIDE CIRCULATOR

2 A. E. Paladino, "Temperature Compensated $MgTi_2O_5$ - TiO_2 Dielectrics", J. Am. Ceram. Soc. 54, (3) 1968 (1971).

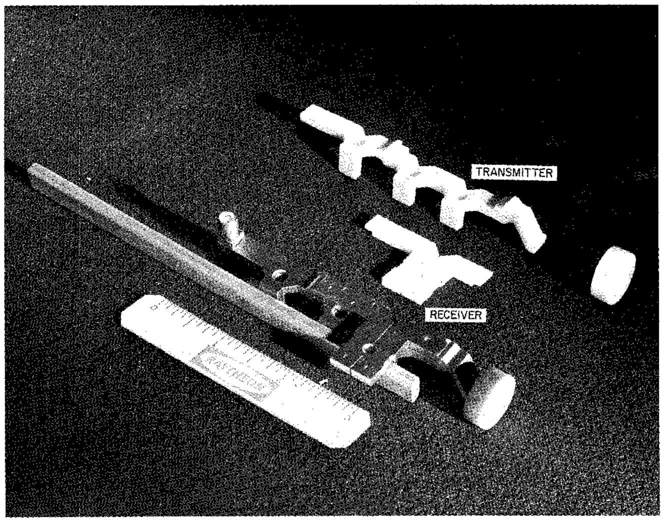

FIG. 3. CERAMIC WAVEGUIDE TRANSISTOR AMPLIFIER CIRCUIT

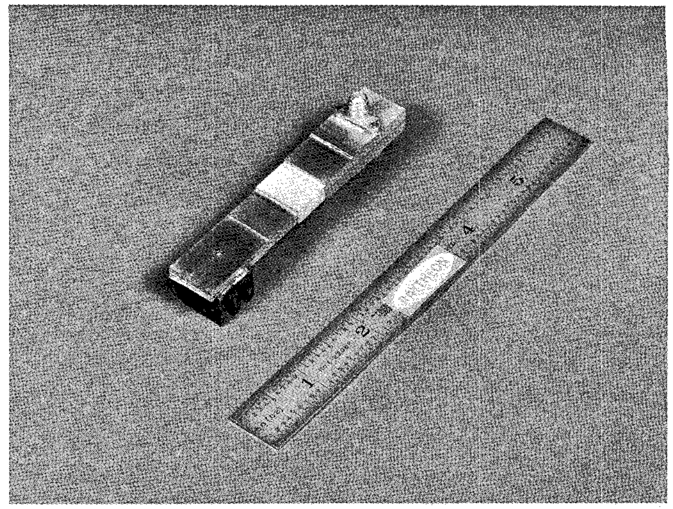

FIG. 4 CERAMIC WAVEGUIDE ACTIVE MODULE

TABLE I

TRANSMISSION LINE COMPARISON AT X-BANK

Line	Symbol	Q	Power Handling	Integ.	Density of Ccts.	Cost
Coax		3	3	4	4	3
Strip		3	3	3	3	2
Microstrip		5	5	2	2	1
Rect. W.G.		1	1	5	5	5
Ceramic W.G.		2	2	2	2	1

TABLE II

MICROWAVE CERAMICS

	Dielectric Constant	Loss Tangent	Temp. Coeff.	Linear Exp.	Thermal Conductivity	Hardness Moh's
Teflon Fiberglass	2.5	10^{-3}	-515	80	low	soft
Quartz	3.8	10^{-4}	+20	8	.02	7
Mg. Silicates	4.5-5	10^{-3}	-	3-10	.006	6-8
Beryllia	6.1	10^{-4}	+50	8	.4	9
Alumina	9.8	10^{-4}	+150	8	.05-.08	9
Mg. Titanates	24	7×10^{-4}	+6	7	-	7
Barium Tetratitanate[5]	37.8	6×10^{-4}	-53	9	-	7

[5] D. W. Readey, E. A. Maguire, C. P. Hartwig, D. J. Massé, "Microwave High Dielectric Constant Materials", Final Technical Report, ECOM 0455F, June 1971.