[5] A. R. Koelle, S. W. Depp, and R. W. Feyman, "Short range radio telemetry for electronic identification using modulated backscatter," *Proc. IEEE*, vol. 63, pp. 1260–1261, Aug. 1975.
[6] R. J. King, "Error analysis of a phase insensitive coherent (homodyne) detector," submitted to *IEEE Trans. Instrum. Meas.*
[7] ——, "Microwave electromagnetic nondestructive testing of wood," in *Proc. 4th Nondestructive Testing of Wood Sym.* (Vancouver, WA), pp. 121–134.

R. J. King (S'60–M'60–SM'75), photograph and biography not available at the time of publication.

Y. H. Yen, photograph and biography not available at the time of publication.

Short Papers

The Thermal Dielectric Quotient for Characterizing Dielectric Heat Conductors

HAROLD A. WHEELER, FELLOW, IEEE, AND RICHARD A. LODWIG

Abstract—**If a piece of dielectric is mounted between two conductors, the resulting thermal conductance and electrical capacitance are related by their quotient which is a property of the material, independent of the size and shape. This quotient is expressed in watts per (picofarad × kelvin). It is helpful in the selection of a material for conducting heat while adding least capacitance. For example, a beryllia ceramic block of 1 pF can conduct about 4 W/K. The highest is a diamond of unusual perfection, about 40 W/K. A table and a nomogram give these properties for a variety of materials.**

A dielectric material may also be required to serve as a heat conductor. It may even be added for providing heat conduction at a particular location with the least shunt capacitance. There is proposed a composite rating termed the "thermal dielectric quotient," which has been found helpful in the selection of a material for this purpose.

The thermal dielectric quotient (TDQ$=T$) is defined as the thermal conductance (G) divided by the electrical capacitance (C) in a material filling some space between two conductor faces. The respective field patterns are known to be alike, so this quotient is independent of size and shape. Therefore, it is a property of the material. The TDQ is then equal to the thermal conductivity (K) divided by the electrivity (electrical permittivity). If these are expressed in compatible units (such as the MKS rationalized system) only the essential quantities remain.

$$\text{TDQ}=T\left(\frac{\text{watts}}{\text{picofarads}\times\text{kelvins}}\right)=\frac{G\left(\dfrac{\text{watts}}{\text{kelvins}}\right)}{C(\text{picofarads})}$$

$$=\frac{K\left(\dfrac{\text{watts}}{\text{meters}\times\text{kelvins}}\right)}{(8.85\,k)\left(\dfrac{\text{picofarads}}{\text{meters}}\right)}.$$

TABLE I
THERMAL CONDUCTIVITY CONVERSION FACTORS FOR MKS–KELVIN UNITS FROM OTHER UNITS

Notes:
1 gram-calorie = 4.18 joules
1 BTU = 252 gram-calories = 1055 joules
1 kelvin = 1.8 degrees F

The MKS unit, $\frac{\text{1 watt}}{\text{meter x kelvin}}$

may alternatively be stated, $\frac{\text{1 milliwatt}}{\text{mm x kelvin}}$

A.	(CGS)	$1\ \frac{\text{gram-calories}}{\text{seconds x cm x kelvins}}$	= 418	$\frac{\text{watts}}{\text{meters x kelvins}}$
B.	[6]	$1\ \frac{\text{watts}}{\text{cm x kelvins}}$	= 100	$\frac{\text{watts}}{\text{meters x kelvins}}$
C.	[8]	$1\ \frac{\text{watts}}{\text{inches x kelvins}}$	= 39.4	$\frac{\text{watts}}{\text{meters x kelvins}}$
D.	(FPH)	$1\ \frac{\text{BTU}}{\text{hours x feet x degrees F}}$	= 1.73	$\frac{\text{watts}}{\text{meters x kelvins}}$
E.		$1\ \frac{\text{BTU x inches}}{\text{hours x sq.ft. x degrees F}}$	= 0.144	$\frac{\text{watts}}{\text{meters x kelvins}}$

The capacitance is expressed in picofarads to give a convenient number; then the electrivity is (8.85 k) pF/m in which k is the material dielectric constant relative to free space. (The kelvin is the most recently adopted term for one degree Kelvin or absolute or Celsius or Centigrade. This unit is strictly not an MKS unit, but is an accepted supplement to that system.)

The simplicity of the units in which the TDQ is expressed is in contrast to the confusion of thermal units in the literature, the only one retained being the temperature difference of the two conductor faces. This simplicity is enabled by assuming faces that are perfect electrical conductors and are perfect thermal conductors. This assumption is valid in some cases, and the TDQ may still be helpful in other cases.

Table I gives, for reference, the factors needed for converting thermal conductivity (K) in various units to the MKS units used herein.

The nomogram in Fig. 1 is chosen for a comparative presentation of the subject properties of typical solid dielectric materials. Each material is represented by a straight line determined by the thermal and electrical properties, which then intersects another scale at the resulting TDQ.

Manuscript received May 11, 1981; revised July 13, 1981. This work was started at Wheeler Laboratories, Inc., Smithtown, NY 11787.
H. A. Wheeler is with Hazeltine Corporation, Greenlawn, NY 11740.
R. A. Lodwig was with Wheeler Laboratories (subsidiary of Hazeltine Corporation), Smithtown, NY. He is now with the Federal Systems Division of International Business Machines, Inc., Gaithersburg, MD 20760.

0018-9480/81/1100-1231$00.75 ©1981 IEEE

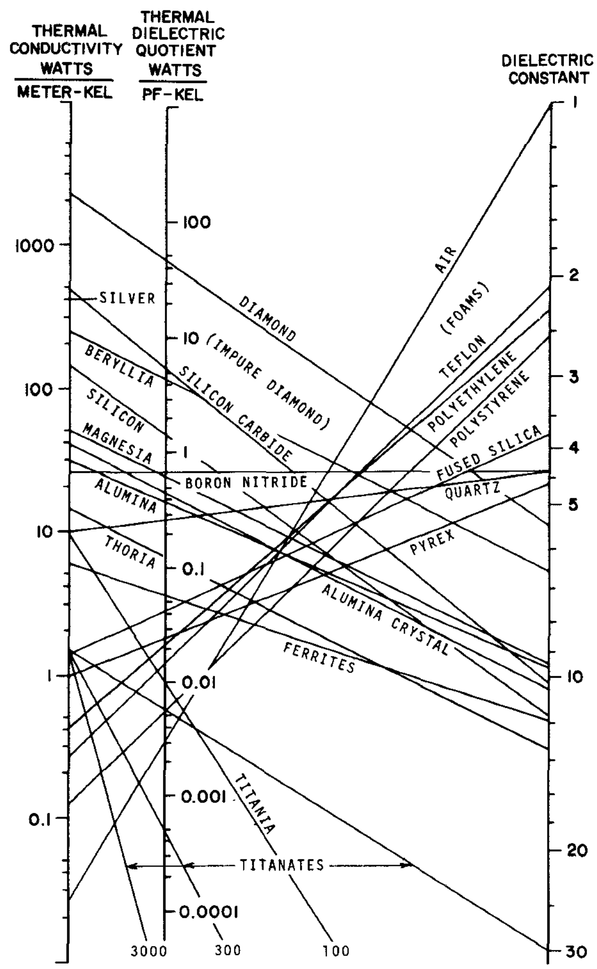

Fig. 1. Nomogram of thermal dielectric quotient.

Table II gives all three properties for each material represented on the nomogram. The collection of the thermal and electrical properties is laborious, since they are scattered over the literature and the reporting may be suspect. Also some of the materials require special description, such as the purity of diamond or the density of a pressed or sintered body. An attempt has been made to select reliable information and, in a case of widely different reports, to choose a typical or representative value. For crystals, the highest purity is reported, and the values are averaged for different axes. For foams of low k, only the bounds are reported (air and the solid material). All values are given for temperatures at or near room conditions.

The lines in Fig. 1 show not only the order of TDQ of various materials, but also the order of the thermal and electrical properties involved. Pure diamond has come to be appreciated as the one material offering (at room temperature) thermal conductivity much higher than silver and copper, the metals of highest electrical conductivity. Beryllia ceramic has a TDQ nearly the highest of all others, and is in increasing use for this property at a reasonable cost. Silicon is the highest of semiconductor materials in common use. Glasses are lower, and plastics still lower. The lowest are titanium compounds of high k.

The materials of higher TDQ are the ones preferred if a block is added for heat conduction, especially if added capacitance is detrimental at that location.

Beryllia ceramic excels as a low-cost practical material of high

TABLE II
THE DIELECTRIC MATERIALS SHOWN ON THE NOMOGRAM

No.	Description	Diel. Const.	Thermal Conduc. watts / m × kel	Thermal Diel. Quotient watts / pf × kel
1	Air (lower bound of foams)	1	0.025	0.003
2	Teflon	2.1	0.25	0.014
3	Polyethylene	2.3	0.4	0.020
4	Polystyrene	2.55	0.12	0.005
5	Silica (fused)	3.8	1.4	0.04
6	Boron nitride (pressed)	4.4	25	0.6
7	Silica (crystal, quartz)	4.4	10	0.26
8	Glass (pyrex)	4.6	1	0.025
9	Diamond (crystal)	5.5	2200	45
10	Beryllia (ceramic 99.5%)	6.6	250	4
11	Magnesia (ceramic 99.5%)	9.5	50	0.6
12	Alumina (ceramic 99.5%)	9.6	30	0.35
13	Silicon carbide (hex. crystal)	10.2	500	5
14	Alumina (crystal, ruby, sapphire)	10.5	40	0.4
15	Silicon (crystal)	11.8	150	1.4
16	Ferrites (typical)	12	6	0.06
17	Thoria (ceramic 99.5%)	13.5	14	0.12
18	Titanates (low k)	30	1.5	0.005
19	Titania (crystal, rutile)	100	10	0.01
20	Titanates (medium k)	300	1.5	0.0005
21	Titanates (high k)	3000	1.5	0.00005
22	Silver, copper (reference)	∞	400	0

TDQ. A block of 1 pF can conduct 4 W/K. A 4-mm cube has $8.85 \times 6.6 \times 0.004 = 0.23$ pF so it can conduct 1 W/K.

If relying on a dielectric for high thermal conductivity, the face conductors should be very close to the dielectric. The effect of a small airgap can be computed, and can be reduced by filling the gap with silicone grease. Presumably, any gap is avoided in printed-circuit or thin-film techniques.

Fig. 1 covers substantially the entire range of TDQ available in materials. The range is about 60 dB. In a "weak-current" circuit (microamperes, microvolts, and picowatts) there is likely to be no problem of heating. However, there is an intermediate range (milliamperes, millivolts, microwatts) where there may be a problem in a very small circuit if the the TDQ is near the bottom of the scale.

The TDQ is particularly helpful in microwave circuits where heat is generated in a small space and must be conducted from an insulated conductor to the shield conductor. In typical cases, the heat may be generated by the average power through a transmission line or by the dissipation in a local device such as a solid-state diode or transistor. In the latter case, a dielectric block may be added to conduct the heat away at a point where added capacitance is undesirable or detrimental. The concept of TDQ was developed a few years ago in the design of a printed circuit including high-power switching diodes.

In general, a microwave circuit includes some capacitance in its design. If a value of capacitance is specified, it can be realized in various configurations. Where it is realized in a dielectric material, the TDQ is a measure of the thermal conductance, regardless of the configuration. For example, a quarter-wave stub of 50-Ω strip line (for one frequency) has a known capacitance, regardless of the configuration and material that may be chosen, so its thermal conductance can then be computed from the TDQ. A desired value of thermal conductance may or may not be obtainable with a practical material.

Acknowledgment

The authors are grateful to some of their associates for helpful information, notably T. C. Hana and H. M. Heinemann. Also they are grateful to the IEEE reviewers who offered a correction to the first manuscript. In addition to the credited references, it is notable that the bulletins from suppliers show a steady trend toward complete and reliable information; we would urge that the MKS units be standardized for all purposes. Future bulletins might well include the TDQ as a significant property of an insulating material, especially if intended for high-frequency applications with high power density.

References

[1] "Properties of solid insulating materials," *Gen. Radio Experimenter*, vol. 14, no. 1, pp. 6–7, June 1939. (Dielectric and thermal.)
[2] *American Institute of Physics Handbook*, 2nd ed, 1963. (Thermal conductivity, R. L. Powell, pp. 4-76–4-101.)
[3] G. A. Slack, "Thermal conductivity of silicon, silicon carbide and diamond," *J. Appl. Phys*, vol. 35, pp. 3460–3466, Dec. 1964.
[4] Chemical Rubber Co., *Handbook of Chemistry and Physics*, 48th ed., 1967. (Thermal conductivity, pp. E-2–E-11.)
[5] A. S. Grove, *Physics and Technology of Semiconductor Devices.* New York: Wiley, 1967. (Dielectric and thermal properties of materials.)
[6] R. C. Levine, "Determination of thermal conductance of dielectric-filled strip transmission line from characteristic impedance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, pp. 645–646, Nov. 1967. (One relation between thermal and electrical properties. Not MKS units.)
[7] ITT, *Reference Data for Radio Engineers*, 5th ed, 1968.
[8] G. Klein, "Thermal resistivity table simplifies temperature calculations," *Microwaves*, vol. 9, no. 2, pp. 58–59, Feb. 1970. (Confusion by use of inverse conductivity and various units other than MKS.)
[9] C. A. Harper, Ed., *Handbook of Materials and Processes for Electronics.* New York: McGraw-Hill, 1970. (Dielectric and thermal properties.)
[10] L. I. Maissel and R. Glany Eds., *Handbook of Thin Film Technology* New York: McGraw-Hill, 1970. (Dielectric and thermal properties of substrate materials.)
[11] "1972 materials selector, " *Materials Eng.*, vol. 74, no. 4, Sept. 1971. (Excellent tables.)
[12] R. L. Powell, correspondence, NBS survey on thermal conductivity; 1972. (Diamond, silicon, other crystals.)
[13] M. Neuberger, *Handbook of Electronic Materials, Vol. 5, Group IV Semiconducting Materials.* New York: Plenum, 1971. (Diamond, germanium, silicon, silicon carbide.)

Planar Broad-Band 180° Hybrid Power Divider/Combiner Circuit

MAHESH KUMAR, MEMBER, IEEE, RAYMOND J. MENNA, MEMBER, IEEE, AND HO-CHUNG HUANG, SENIOR MEMBER, IEEE

Abstract—A planar broad-band 180° hybrid is presented. The hybrid is realized using a 3-dB 90° hybrid and a 0-dB 90° tandem hybrid. An interdigitated version of the hybrid fabricated on alumina substrate performed well over the 4–8-GHz band. The hybrid has an insertion loss of 0.5 dB, phase imbalance of ±7°, and an isolation of better than 18 dB over the band.

Manuscript received April 7, 1981; revised July 13, 1981 This work was supported by the Office of Naval Research, Arlington, VA, under Contract N00014-79-0568, and monitored by M. N. Yoder.
The authors are with RCA Laboratories, David Sarnoff Research Center, Princeton, NJ 08540.

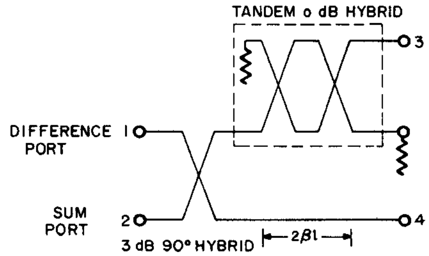

Fig. 1. Schematic of a 180° hybrid.

I. Introduction

In the past, 180° hybrids have been extensively used in balanced mixers, switching networks, phase shifters, and push–pull amplifiers. The recent interest in monolithic GaAs integrated circuits has opened the need for a 180° planar hybrid compatible to monolithic integration on GaAs substrates.

Conventional hybrid rings have been used as 180° hybrids. The hybrid ring has a narrow bandwidth. Reflection-type 180° hybrids have been reported in literature [1]. The problem with this kind of hybrid is the practical difficulty of realizing a good short or open circuit over wide band of frequencies. The commercially available 180° hybrids use a tandem connection of two couplers using broadside coupling [2], [3]. This is a multilayer structure and can be realized using striplines only. Recently, a 3-dB 180° hybrid has been reported [4] which uses a slot line–microstrip coupling. The abovementioned structures for 180° hybrids are not planar, and not easily compatible to monolithic circuit fabrication

This paper presents an analysis and experimental results of a broad-band 180° planar hybrid. This hybrid is a four-port device with two input ports and two output ports. One of the input ports is designated as the sum port and the other as the difference port. A signal fed into the sum port or the difference port is divided into two signals of equal amplitude with a phase difference of 0° or 180°, respectively. This hybrid has been realized using a 3-dB interdigitated, 3-dB 90° hybrid, and a 0-dB 90° interdigitated tandem hybrid. The latter hybrid introduces an additional 90° phase shift which is independent of frequency. The analysis of the circuit is presented in Section II. The hybrid has been designed and fabricated on alumina substrate for *C*-band operation. The experimental results are presented in Section III.

II. Analysis of the Hybrid

The schematic of the hybrid is shown in Fig. 1. It is a four-port device. Ports 1 and 2 are the input ports and ports 3 and 4 are the output ports. When the signal is fed to port 1, the signals appearing at port 3 and port 4 are both 3 dB below the input signal and have a phase difference of 180°. When a signal is fed at port 2, the signals appearing at ports 3 and 4 are both 3 dB below the input signal and are in phase. These two cases are considered separately and the analysis is presented for both cases.

Case 1: Input at Difference Port

Let θ be the coupling angle and l be the coupling length. The hybrid is illustrated in Fig. 1. Port 4 has an extra length of transmission line of length $2\beta l$. It will be shown later that the phase difference of the two output signals appearing at ports 3 and 4 is independent of frequency. Assume that a unit amplitude signal is fed at port 1 (port 2 is theoretically isolated), then the