IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. MTT-27, NO. 5, MAY 1979

Microwave Power Combining Techniques

KENNETH J. RUSSELL

Invited Paper

***Abstract*—A review of various techniques for coherently combining microwave power from two or more sources is presented. Emphasis is placed on techniques which combine solid-state power sources. Basic operating characteristics and limitations for the different combiner types are discussed. The performances obtained with the most successful techniques are described. Future trends in combining RF power from solid-state sources are identified.**

OVER THE YEARS there has been great interest in developing techniques for combining power from microwave and millimeter-wave power sources. With the advent of the IMPATT diode as a reliable solid-state microwave source, the search for efficient power combining techniques was given even greater emphasis. The development in 1973 [1] of pulsed X- and Ku-band IMPATT diodes gave interest in power combiner development another boost since, with these diodes, it became evident that a combiner with only a modest number of these devices could fill important radar transmitter applications. Recently, with the development of power FET's in X- and Ku-band, industry-wide interest in combining microwave power transistors has also developed.

Power combining can be considered on two general levels: the device level and the circuit level. Device level combining is accomplished by clustering the devices in a region whose extent is small compared with a wavelength [2]–[4]. Device level combining is generally limited in the number of devices that can be efficiently combined. This paper addresses the combining of microwave power at the circuit level where the combining technique is not limited to placing the diodes in an area small compared to a wavelength. The discussion here will be concerned primarily with one-port diode power combiners operating as oscillators, injection-locked oscillators, or reflection amplifiers. However, each combining technique to be discussed could form the combiner or divider stages of a two-port power combiner for microwave transistors. The combining techniques to be discussed below were chosen as those which have been most successful and/or are currently being actively studied. Similarly, the list of references is not claimed to be complete, and many fine papers may have been omitted. However, the list should be complete enough to provide an initial guide to the interested reader.

Manuscript received June 7, 1978; revised December 5, 1978.

The author is with the Hughes Aircraft Company, Malibu, CA.

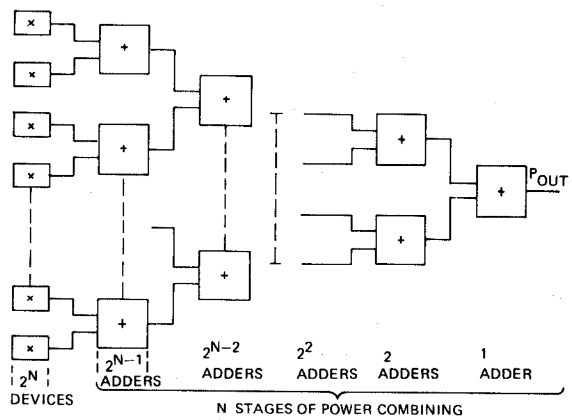

Fig. 1. A corporate structure (or tree) for combining power.

Combining approaches can be separated into two general categories, those which combine the output of N devices in a single step and those which do not. The former are called N-way combiners and will be further discussed in Section II. The latter category of combiner is the simpler and more widely used. It includes the chain (or serial) and tree (corporate) combining structures.

I. Chain and Tree Combining Structures

A corporate [5], [6] structure (or tree) for combining power from two-way adders or combiners is shown in Fig. 1. In principal, with lossless adders, any amount of power could be obtained this way. However, with real adders the losses in the two-way power adders limit the combining efficiency and, therefore, the usefulness of this approach. Fig. 2 illustrates the combining efficiency of the corporate structure versus the number of devices and the loss per adder for the case where equal-loss adders are used. In an amplifier, the gain and bandwidth are similarly decreasing functions of the number of diodes. The number of devices combined in this type of structure is binary, i.e., must equal 2^N where N is a positive integer. Examples of two-way adders (or generally, directional couplers) that could be used in the corporate combining structure are shown in Fig. 3. They all have two features in common: 1) a means of matching the impedance of the input ports to the output port, and 2) a means of isolating the input ports from one another. These circuits have been covered rather thoroughly in the literature [7]–[11] and will not be treated further here.

A chain or serial [12], [13] combiner is shown in Fig. 4. Here, for an N-stage combiner each successive stage or

0018-9480/79/0500-0472$00.75

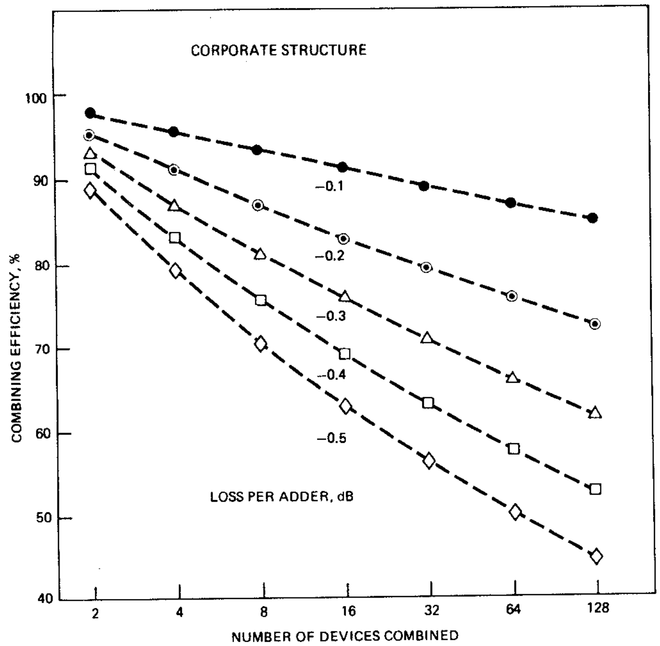

Fig. 2. Combining efficiency for a corporate combining structure.

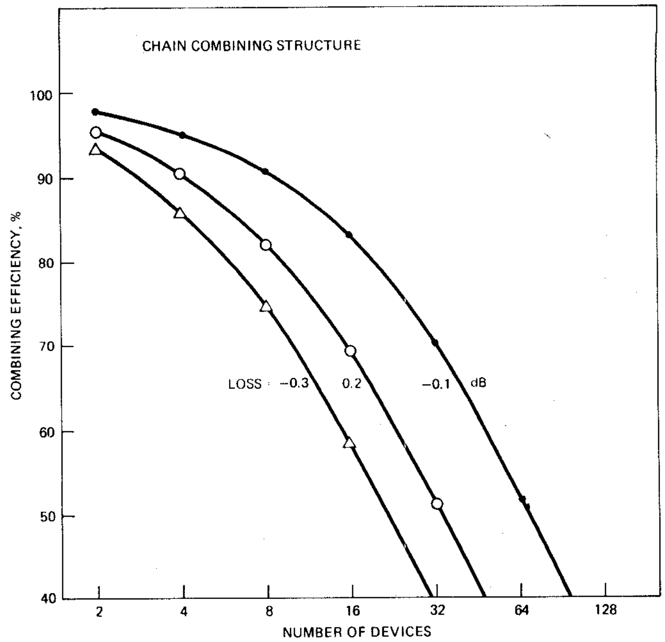

Fig. 5. Combining efficiency for the chain combining structure. Loss in decibels refers to the loss in each power path in each stage's coupler.

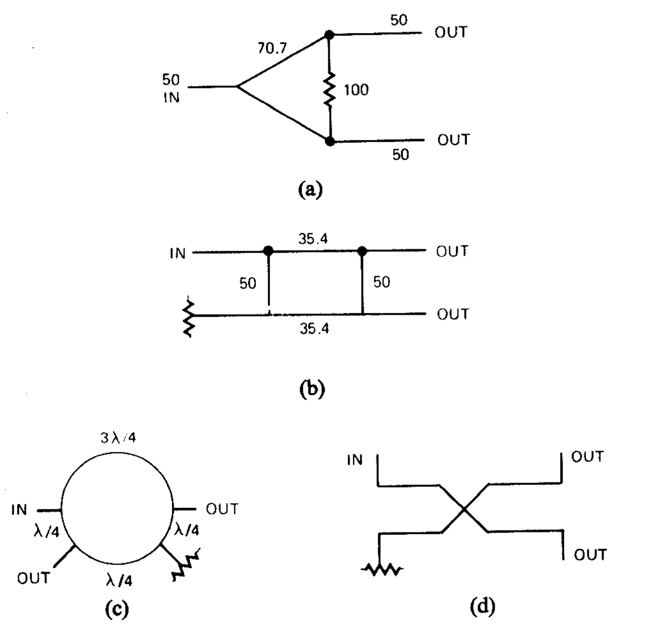

Fig. 3. Common forms of power combiner couplers. (Strictly speaking, dividers are pictured here; if input and output roles are interchanged, they become combiners.) (a) Wilkinson combiner (2-way). (b) Branch line 90° hybrid. (c) Rat race. (d) Coupled line directional coupler.

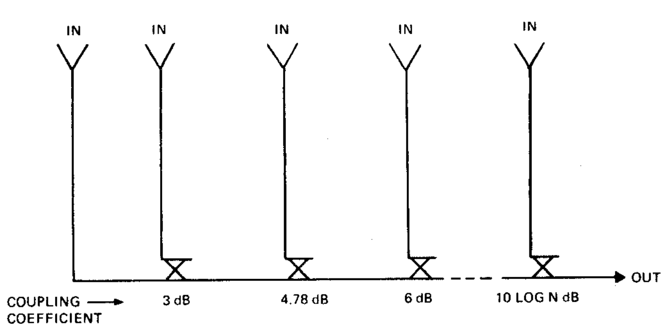

Fig. 4. A chain combining structure.

coupler adds $1/N$ of the output power to the output. The number of the stage determines the required coupling coefficient for that stage, as indicated in the figure. The choice of coupling coefficients is also affected by the loss in the coupler. Neglecting losses, the necessary coupling coefficient for the Nth stage is $10 \log_{10} N$ in decibels. One advantage of the chain configuration is that another stage can be added by simply connecting the new source to the line after the Nth stage through a coupler with $10 \log_{10}(N+1)$ coupling coefficient. The chain combining approach is nonbinary, and, in principal, any number could be combined. Losses in the couplers reduce the combining efficiency and bandwidth attainable with this approach. Also, it is difficult to build the couplers with the high coupling coefficients necessary when larger numbers of devices are to be combined. The combining efficiency E_c can be estimated by assuming that the losses in each coupler are divided equally between the two paths of power flow through the coupler. (A coupler, when viewed as a power splitter, divides the input power equally or unequally, depending on its design, into two output ports. The roles of input and output ports are interchanged when the coupler is used as an adder, as in Fig. 4, but the two paths of power flow are the same although the direction of flow is reversed.) The relation

$$E_c = \frac{1}{N}\left[10^{(N-1)L/10} + \sum_{k=0}^{N-2} 10^{(1+k)L/10}\right]$$

is shown plotted in Fig. 5 for several values of loss L per path.

The chain or tree combining structures can be and have been realized in a number of different transmission media such as microstrip, coaxial line, or waveguide. The choice

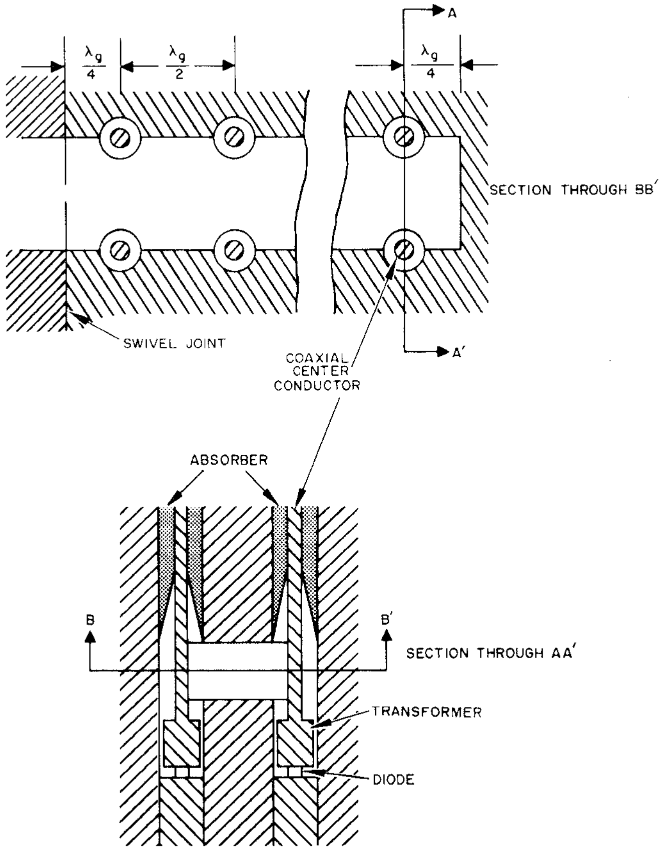

Fig. 6. Two cross sections of the Kurokawa waveguide combiner.

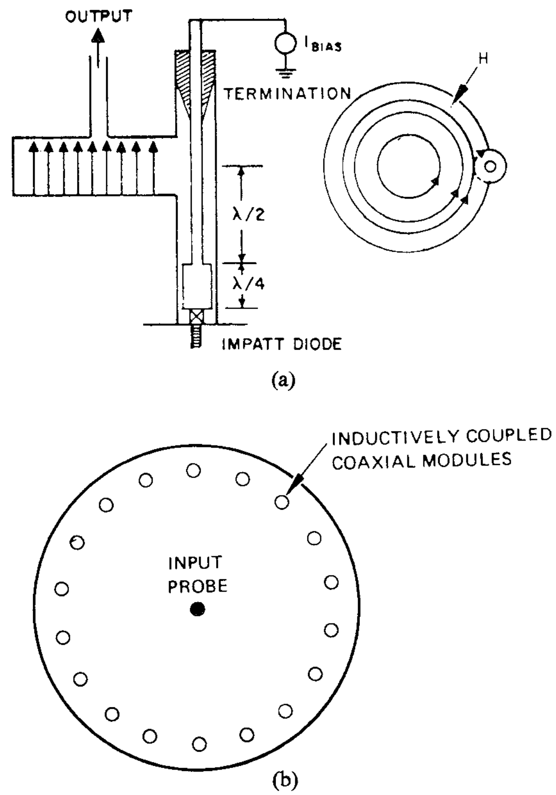

Fig. 7. Cylindrical resonant cavity combiner. (a) A single coaxial circuit module illustrating magnetic coupling to TM_{010} cavity. (b) Top view of resonant cavity showing module positions around periphery.

of the transmission media impacts heavily on the resulting size and circuit losses with microstrip tending to be compact and waveguide tending to be lowest loss.

II. *N*-Way Combining Structures

The *N*-way combining structure sums the power of the *N* devices directly in one step without having to proceed through several combining stages. This opens the possibility of such structures having high combining efficiencies since the power generated does not have to pass through several stages of combining. Some *N*-way combining structures do fulfill that promise while others fail for a variety of reasons.

The *N*-way combiners can be further divided into two categories, cavity and nonresonant combining structures.

A. Cavity Combining Structures

In this category of power combiners, the sum of output powers from a number of devices is obtained by coupling their outputs to a single resonator. Two notable examples of this technique have been successfully operated.

Fig. 6 illustrates a waveguide version described by Kurokawa and Magalhaes in 1971 [14]. Using this approach, the power from twelve IMPATT diode oscillators was combined. Each diode is mounted at one end of a stabilized coaxial line which is coupled to the magnetic field at the sidewall of a waveguide cavity. To properly couple to the waveguide cavity, the coaxial circuits must be located at the magnetic field maxima of the cavity, and, therefore, the diode pairs must be spaced one-half-wavelength (λ_g) apart along the waveguide, as noted in Fig. 6. The combiner described by Kurokawa and Magalhaes operated at 9.1 GHz and produced 10.5-W CW output power as an oscillator. In a later paper Kurokawa reported the operating efficiency to be 6.2 percent with good stability and no spurious output.

Perhaps the most successful and, therefore, the most widely used diode combining technique for combining large numbers of devices is the cavity combining technique invented by Harp and Stover and described by them in 1973 [16]. The technique can be explained by reference to Fig. 7. In this technique a number of coaxial modules, similar to those described by Magalhaes [17], are placed around the circular periphery of a cylindrical cavity resonant in a TM_{0N0} mode (a TM_{010} mode is indicated in the figure). In these modes the magnetic field is a maximum at the cavity wall and couples to the center conductor of the coaxial modules inducing a high impedance in series with the coaxial line. The coaxial modules incorporate quarter-wave transformers at the diode end (to match the low impedance of the IMPATT diodes to the cavity impedance) and are terminated in a material that serves as a microwave absorber and a dc insulator. The coaxial module center conductors furnish bias to the IMPATT diodes. The TM_{0N0} modes have a maximum of the electric field at the central axis of the combiner, and output is obtained from the combiner by placing a probe

TABLE I
RESONANT-CAVITY POWER-COMBINER PERFORMANCE

Frequency	X Band									K_a Band
Combiner Capacity, Diodes	4	8			16			32		8
Cavity Mode	TM_{010}	TM_{010}			TM_{010}			TM_{020}		TM_{010}
Diode Type	Si, pulsed	Si,cw	GaAs,cw	Si, pulsed	Si,cw	GaAs,cw	Si, pulsed	Si,cw	Si, pulsed	Si,cw
Maximum oscillator Power, W	51.8 (peak)	8	34.2	105# (peak)	13.8	60	218# (peak)	24.5	280*# (peak) 385*□#	10
Mechanical tuning range, GHz		>0.5			0.3			0.3		1
Injection locked oscillator BW (MHz) at 10 dB gain		100			33			26		160
Efficiency, %	10		24.5		6.2	21	10		7.5	9 to 10
Amplifier Operation:										
Output power, W	32.3	12			20			32		
Gain, dB	7	3		3	3		8.6	6		
Bandwidth, MHz	275	400		900	125		105	80		

*Obtained with 32 diodes at reduced bias. □ Obtained with the combiner as the final stage in a 5-stage amplifier

Measured with 1 μsec pulse width and 25% duty cycle.

(which is an extension of the output coaxial transmission line) at this point.

An important feature of the cylindrical resonant cavity combining technique is that, since the cavity fields are azimuthally symmetric, there is no minimum spacing between coaxial modules. Therefore, the limit on the number of devices that can be placed around a given cavity is determined by the diode size. Typical spacing between modules using packaged X-band IMPATT diodes is less than 0.2 in. Another important feature of this combining technique is that the coaxial modules are terminated with a microwave absorbing material. Consequently, at all frequencies removed from the cavity resonance, the IMPATT diode sees a real impedance higher than its negative resistance and is, therefore, stable. This feature is important when the combiner is operated as an amplifier at a high drive level since it prevents the formation of idler resonances below the operating frequency and thereby avoids parametric instabilities.

Combining a larger number of devices than can be put around the periphery of a cylindrical cavity resonant in the TM_{010} mode may be done by using devices with smaller package sizes or by increasing the diameter of the circle on which the devices are located. In the latter case a larger cavity resonant in a TM_{0N0} mode with $N \geqslant 2$ can be designed (N here describes the number of field variations in the cavity mode). When this is done, however, cavity modes other than those desired can be generated if provision is not made for their prevention. This can easily be done since TM_{0N0} modes have only radial currents while most of the undesirable modes have azimuthal current variation. Radial slots filled with a microwave absorber can then be used to suppress the azimuthal modes (which would have RF current crossing the slots) while leaving the TM_{0N0} modes unaffected. TM_{0N0} modes other than the one desired are far enough separated in frequency from the mode of interest that the coaxial module terminations suppress them.

The cylindrical resonant cavity combining technique has received considerable development and application support in recent years [18]–[21]. The combining technique has been applied at frequencies in C, X, Ku, and Ka bands. Combiners of this type have operated as oscillators, injection-locked oscillators, and amplifiers. Most development work has been done in X band where various TM_{010}, TM_{020}, and TM_{040} cavity combiners have been built and tested. The combiners have operated with silicon CW single-drift, silicon CW double-drift, silicon pulsed double-drift, and GaAs CW modified-Read IMPATT diodes at Hughes Research Laboratories (HRL). Table I summarizes some of the performance data obtained at HRL. Combining efficiency for these combining structures is difficult to define and measure since the efficiency of these structures is so high. If one compares the output of one of the N-diode combiners with the sum of the output of the N diodes tested individually in optimized single-diode circuits, one often calculates "combining efficiencies" over 100 percent. This happy occurrence obtains because the combining structure is a very efficient circuit, and, for a given cavity size, the combining efficiency can empirically be demonstrated to increase with the number of diodes. A simple loss analysis in which the losses in the combiner are due to losses L_1 in the cavity and output coaxial line, and losses L_2 in each coaxial module indicate that the combining efficiency for a given cavity size is independent of the number of devices combined. In this example the output from each coaxial module is $P_i\ 10^{0.1L_2}$ where P_i is the power generated by the diode. Then the power output from all the modules is $NP_i\ 10^{0.1L_2}$. Since NP_i is the power generated by the diodes, the combining efficiency E_c is

$$E_c = 10^{(L_1+L_2)/10}$$

which is independent of the number of devices being combined. This simple model does not, of course, include the various dynamic effects (different cavity loading, etc.) incurred when changing N. Because of the uncertainty in meaning of combining efficiency (because P_i in the above analysis cannot be reliably determined), it has become more desirable to show the efficiency of conversion of bias power to RF power (as in Table I) when discussing the performance of these combiners. Their efficiencies can then be compared with those of other single- or multiple-diode circuits which use similar diodes. At present, the development of TM_{0N0} combiners with $N \geqslant 2$ is behind the TM_{010} because of less interest in them in the past and their greater complexity. However, the 7.5-percent efficiency of the 32-diode combiner which uses a TM_{020}-mode cavity as listed in Table I indicates that this should not long be the case. The performance shown in the table for 32 pulsed silicon diodes was obtained from a combiner with 32 coaxial modules which is being developed for use as a 64-diode combiner (with two diodes per module) in the final stage of a 30-dB gain amplifier [23]. Combiners with cavities operating in the TM_{040} mode [18], [22] have yet to demonstrate their promise, although the causes for this do not seem inherent in the combining technique.

When used as an amplifier, the cylindrical resonant cavity combining technique has demonstrated a 1-dB down bandwidth of about 9 percent for 3-dB gain at 10 GHz. This was obtained from an 8-diode combiner specifically designed for broader bandwidth and using a TM_{010}-mode cavity. The bandwidth of the cylindrical resonant cavity combiner is limited by the cavity Q (large cavity Q implies a small bandwidth). The cavity Q of a given diameter cavity can be lowered (and the bandwidth increased) by decreasing the cavity height. This technique was used with the wider bandwidth 8-diode combiner mentioned above.

B. Nonresonant Combining Structures

A number of nonresonant combining techniques have been proposed. Because of their nonresonant structure, they offer the prospect of wide-band amplifier operation.

One of the oldest and best known of these structures is the Wilkinson N-way combiner [10]. The concept for the combiner is illustrated in Fig. 8. The input ports (of impedance Z_0) feed into N output lines of characteristic impedance $\sqrt{N}\ Z_0$ which are one-quarter-wavelength long. Isolation between the N-ports is accomplished by

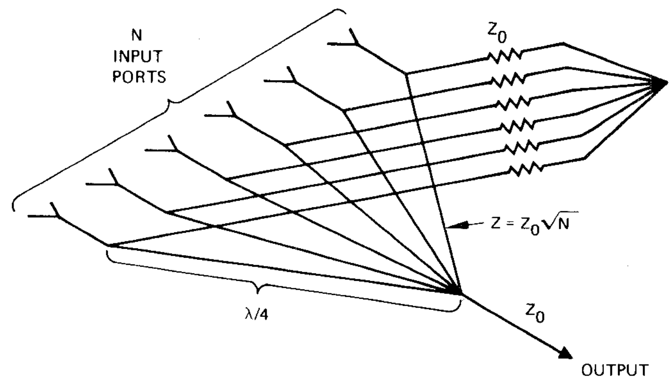

Fig. 8. Wilkinson N-way combiner.

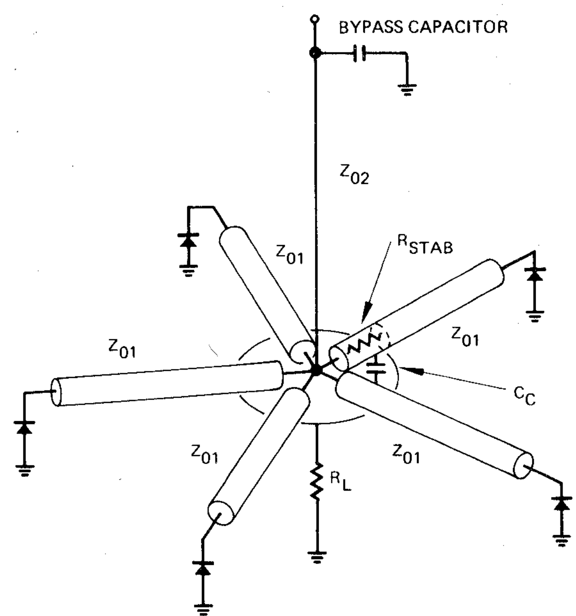

Fig. 9. Rucker's 5-way combiner.

means of the resistive star connected to the N-ports. The best known version of the Wilkinson circuit is the two-way combiner shown in Fig. 3. The principal problem with the Wilkinson approach at high frequencies is that it is generally not possible to connect sufficiently powerful isolation resistors in the manner shown when $N > 2$. Nor can the resistors be connected as shown when planar circuits are used (except for the two-way Wilkinson). Accordingly, a number of modifications of the concept have been suggested over the years [24]–[26]. Although operation of some of these circuits has been demonstrated in transistor power combiners (a six-GaAs-FET-transistor amplifier version of the approach described in [25] has yielded a 10-percent bandwidth and a 78-percent combining efficiency in X band), their use has not become widespread.

Another combining technique with demonstrated success was described by Rucker [27] and later analyzed by Kurokawa [28]. This technique, illustrated in Fig. 9 for a 5-diode oscillator, has a number of coaxial transmission lines, each approximately one-quarter-wavelength long, terminated by a device and arranged radially about a common bias network and a common output network. A

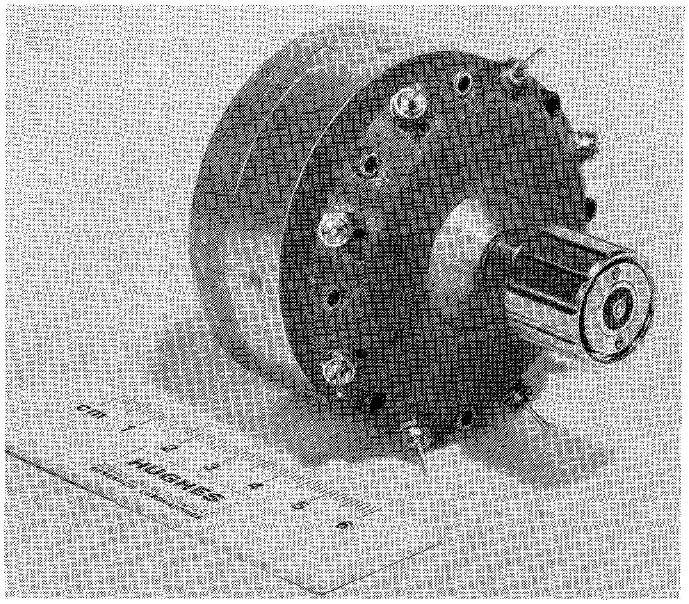

Fig. 10. 8-diode conical combiner.

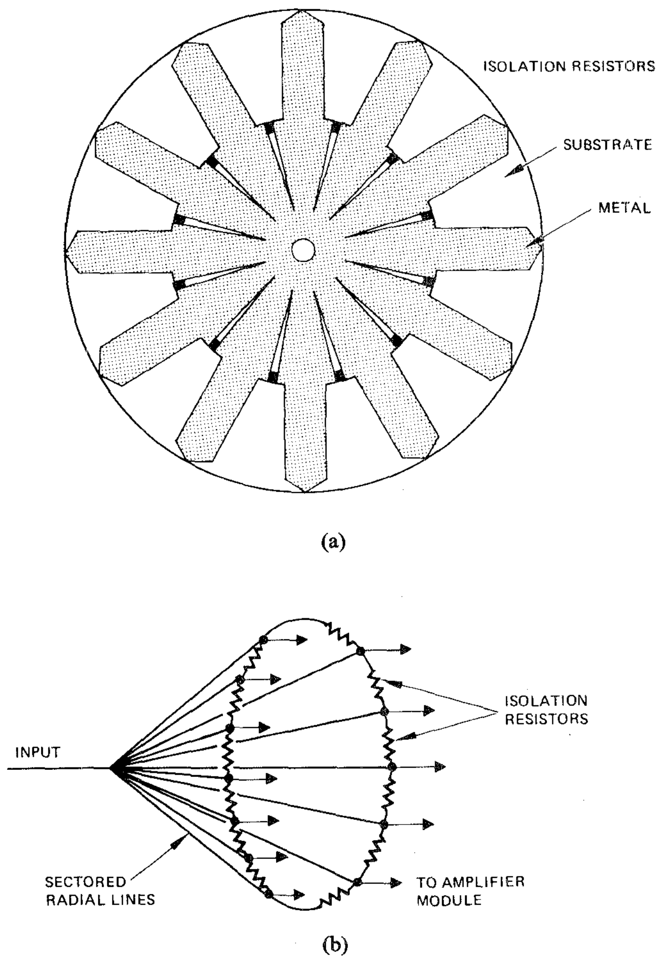

Fig. 11. Dielectric-filled microstrip-radial-line combiner. (a) 12-way divider/combiner circuit fabricated on a fused silica substrate. (b) Equivalent circuit.

resistor R_s is incorporated into each coaxial center conductor to eliminate instabilities commonly observed with multiple-oscillator arrangements. The capacitance C_c between the output coupling disk and each coaxial center conductor provides the necessary coupling to the common load R_L. The bypass capacitor in the bias network is located approximately one-quarter-wavelength from the central hub of the oscillator. The 5-diode oscillator operated over a 7–9-GHz range of frequencies. Maximum bias-to-RF-power conversion efficiency was approximately 5 percent using diodes which approached 10-percent efficiency in single-diode circuits.

Several experimenters have investigated using nonuniform transmission lines [29] or radial transmission lines [17], [30] to serve as power dividing and combining structures. Using this technique, the input power is divided among the devices by these lines (for a divider) and the output impedance to the devices is determined by the transmission lines variable characteristic impedance which is a decreasing function of length or diameter of the line. Fig. 10 illustrates an X-band 8-diode combiner [29] which uses a conical transmission line to affect the power division/combination. This combiner has a coaxial transmission line which makes the transition into a conical transmission line. IMPATT diodes are symmetrically placed in a circle about the axis of and near the end of the conical line. This combining technique is presently under development as a broad-band IMPATT diode combiner and has demonstrated a 15-percent bandwidth (1 dB down) with 6-dB gain operating in X band.

An example of a radial line combiner which has recently been developed for use as a 12-way transistor combiner for X band is shown in Fig. 11 [30]. The combiner uses dielectric-filled sectored radial transmission lines for the power divider/combiner structures. One of these lines is shown in Fig. 11. Port-to-port isolation is accomplished with tantalum thin-film isolation resistors deposited between adjacent ports. The radial transmission line is accomplished on microstrip with fused silica substrate. Coaxial transmission lines with abrupt, stepped transitions to the microstrip radial lines are used for input and output. The combiner has demonstrated a combining efficiency of 87.4 percent and a 1-dB bandwidth of 20 percent at 8.5 GHz operating as an amplifier.

III. Future Trends

Emphasis in diode combiner development for the future seems to be devoted to moving the technology developed in X and Ku bands into the higher millimeter-wave regions or in developing new combiner technology which would be applicable there. Emphasis in diode combining in the lower frequency ranges is now being placed in developing diode power combiner amplifiers with wide bandwidths since narrow-band amplifier and oscillator applications appear to be satisfied by the cylindrical-resonant-cavity combining technique. Combiner interest in X and Ku bands is now focusing also on transistor amplifiers due to the development of commercial power transistors in that frequency range. The question of "graceful degradation" of solid-state power combiners is being reconsidered. "Graceful degradation" refers to the combiner feature that its output is reduced but not completely lost by the failure of a small number of devices. With present combiners, when a device fails the output is reduced by approximately twice that contributed by the device, rather than just the device power. While this is "graceful degradation" in the sense that output is still being generated, the extra loss is undesirable, and techniques for prevention of the loss are being studied.

References

[1] G. Pfund *et al.*, "Pulsed silicon double-drift IMPATTS for microwave and millimeter-wave applications," *Electron. Lett.*, vol. 9, no. 22, Nov. 1, 1973.

[2] J. G. Josenhans, "Diamond as an insulating heat sink for a series combination of IMPATT diodes," *Proc. IEEE*, vol. 56, p. 762, Apr. 1968.

[3] M. Cowley, "High-power parallel-array IMPATT diodes," *Electron. Lett.*, vol. 7, p. 301, June 1971.

[4] N. W. Cox *et al.*, "Investigations of techniques for combining IMPATT chips," Final Tech. Rep., AFAL-TR-74-329, Jan. 1975.

[5] S. Mizushina, "2^n oscillators combined with 3-dB directional couplers for output power summing," *Proc. IEEE*, vol. 55, p. 2166, Dec. 1967.

[6] H. Fukui, "Frequency locking and modulation of microwave silicon avalanche diode oscillators," *Proc. IEEE*, vol. 54, p. 1475, Oct. 1966.

[7] A. W. Morse, "Modify combiner designs to team high power amps.," *Microwave*, vol. 17, p. 70, Jan. 1978.

[8] S. Cohn, "Shielded coupled-strip transmission line," *IRE Trans. Microwave Theory Tech.*, vol. MTT-3, p. 29, Oct. 1955.

[9] L. Napoli and J. Hughes, "Characteristics of coupled microstrip lines," *RCA Rev.*, pp. 479–498, Sept. 1970.

[10] E. Wilkinson, "An *N*-way hybrid power divider," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 116–118, Jan. 1960.

[11] C. Y. Pon, "Hybrid-ring directional coupler for arbitrary power divisions," *IRE Trans. Microwave Theory Tech.*, vol. MTT-9, p. 529, Nov. 1961.

[12] R. J. Mohr, "A microwave power divider," *IRE Trans. Microwave Theory Tech.*, vol. MTT-9, p. 573, Nov. 1961.

[13] M. Nakajima, "A proposed multistage microwave power combiner," *Proc. IEEE*, vol. 61, p. 242, Feb. 1973.

[14] K. Kurokawa and F. M. Magalhaes, "An *X*-band 10-W multiple-diode oscillator," *Proc. IEEE*, vol. 59, p. 102, Jan. 1971.

[15] K. Kurokawa, "The single-cavity multiple-device oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, p. 793, Oct. 1971.

[16] R. S. Harp and H. L. Stover, "Power combining of *X*-band IMPATT circuit modules," presented at the IEEE Int. Solid-State Circuits Conf., 1973.

[17] F. M. Magalhaes and K. Kurokawa, "A single-tuned oscillator for IMPATT characterizations," *Proc. IEEE*, vol. 58, p. 831, May 1970.

[18] "Microwave power combinatorial development, task 1: 10 GHz amplifier/combiner," Final Tech. Rep., AFAL-TR-75-175, Nov. 1975.

[19] R. S. Harp and K. J. Russell, "Improvements in bandwidth and frequency capability of microwave power combinatorial techniques," presented at the 1974 IEEE Int. Solid State Circuits Conf., Feb. 1974.

[20] K. J. Russell and R. S. Harp, "Power combiner operation with pulsed IMPATT's," presented at the 1975 IEEE Int. Solid State Circuits Conf., Feb. 1975.

[21] "High efficiency solid-state *C*-band generator," Final Tech. Rep., RADC-TR-75-286, Nov. 1975.

[22] R. Mastroianni *et al.*, "An *X*-band IMPATT diode power amplifier for pulsed radar systems," Presented at the IEEE 1977 Nat. Aerospace & Electronics Conf. "NAECON '77," Dayton, OH, May 1977.

[23] K. J. Russell and R. S. Harp, "A multistage high-power solid-state *X*-band amplifier," in *1978 IEEE Int. Solid State Circuits Conf., Dig. of Tech. Papers*, vol. 166, Feb. 1978.

[24] U. H. Gysel, "A new *N*-way power divider/combiner suitable for high-power applications," in *Proc. 1975 IEEE-MTT-S Int. Microwave Symp.*, IEEE Cat. No. 75CH0955-5, p. 116, May 1975.

[25] N. Nagai *et al.*, "New *N*-way hybrid power dividers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, p. 1008, Dec. 1977.

[26] Z. Galani and S. J. Temple, "A broadband planar *N*-way combiner/divider," in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, IEEE Cat. No. 77CH1219-5 MTT, p. 499, June 1977.

[27] C. T. Rucker, "A multiple-diode high-average power avalanche-diode oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, p. 1156, Dec. 1969.

[28] K. Kurokawa, "An analysis of Rucker's multidevice symmetrical oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, p. 967, Nov. 1970.

[29] K. J. Russell and R. S. Harp, "Broadband diode power-combining techniques," Air Force Avionics Lab., Wright-Patterson Air Force Base, OH, Interim Tech. Rep. No. 1, Contract No. F33615-77-C-1022, Mar. 1978.

[30] J. M. Schellenberg and M. Cohn, "A wideband radial power combiner for FET amplifiers," in *1978 IEEE Int. Solid State Circuits Conf., Dig. Tech. Papers*, Feb. 1978.