algebraic methods alone. This may be the main advantage of the present geometrical method.

As reported here, following this geometrical method, two practical systems for automatic measurements of $\bar{z}$ are designed here. One can be used under fixed but adjustable frequency, swept-power conditions, and the other, under swept-frequency, swept-power conditions. The bandwidths of both these systems should be about the same as those of the waveguides themselves if the probe loading is very slight. These systems can be used in either high-power or low-power levels as long as the probes can pick up enough signals without loading the waveguide. Also following this new method, further generalization of the system may be reached. For example, we may use different probe arrangements on a "loop line" for measuring the transfer functions or the scattering matrix of an unknown microwave component, or, we may use more probes to check and to enhance the measurement accuracy.

References

[1] A. L. Samuel, "An oscillographic method of presenting impedance on a reflection-coefficient plane," *Proc. IRE*, vol. 35, pp. 1279–1283, Nov. 1947.

[2] E. L. Ginzton, *Microwave Measurements*. New York: McGraw-Hill, 1957, pp. 303–307.

[3] W. J. Duffin, "Three probe method of impedance measurement," *Wireless Eng.*, pp. 317–320, Dec. 1952.

[4] D. D. King, *Measurements at Centimeter Wavelength*. Princeton, NJ: Van Nostrand, 1952, pp. 197–201.

[5] J. K. Chamberlain and B. Easter, "A technique for the continuous indication of waveguide reflection coefficient, impedance, or admittance," *Proc. Inst. Elec. Eng.*, pp. 696–703, May 1962.

[6] C. J. Hu, "On-line measurements of the fast changing dielectric constant in oil shale due to high power microwave heating," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 38–43, Jan. 1979.

Corporate and Tandem Structures for Combining Power from 3^N and $2N+1$ Oscillators

SHIZUO MIZUSHINA, MEMBER, IEEE, HIROSHI KONDOH, AND MITSUAKI ASHIKI

***Abstract*—The output power from three Gunn oscillators was combined using a short-slot coupler in conjunction with high-level injection locking with the power combining efficiency of about 100 percent at 9.7 GHz. Using the 3-oscillator structure as the building block, we constructed ($3^2=$)9-oscillator corporate structure and ($2\times4+1=$)9- and ($2\times6+1=$)13-oscillator tandem structures to demonstrate power combining efficiencies of 92, 95, and 93 percent, respectively, at 9.6 GHz.**

Introduction

VARIOUS TECHNIQUES for combining power from microwave solid-state sources have been described by many authors over the years [1]–[9]. Some of the techniques, most notably, the single-cavity-multiple-device techniques reported by Kurokawa and Magalhaes [2] and by Harp and Stover [3], have gained practical importance to fulfill a class of communication and radar transmitter requirements during the last several years. Nevertheless, it is always interesting to explore new high-efficiency power combining techniques that would offer possibilities of achieving higher power at higher frequencies. This paper describes a new method of combining power from multiple oscillators using short-slot couplers [10] in conjunction with high-level injection locking.

Manuscript received April 15, 1980; revised July 22, 1980.

S. Mizushina and M. Ashiki are with The Research Institute of Electronics, Shizuoka University, Hamamatsu 432, Japan.

H. Kondoh is with the School of Electrical Engineering, Cornell University, Ithaca, NY 14853.

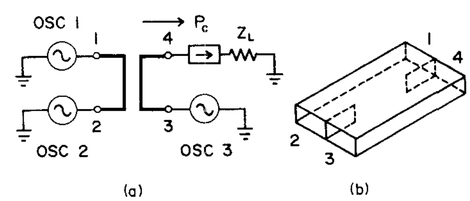

Fig. 1. (a) A 3-oscillator structure using a hybrid coupler. (b) A short-slot coupler used in the present work.

Principles

Three identical oscillators and a matched load are connected to a four-port hybrid coupler to form a 3-oscillator structure, as shown in Fig. 1(a), which is the building block of our power combining structures. The coupler

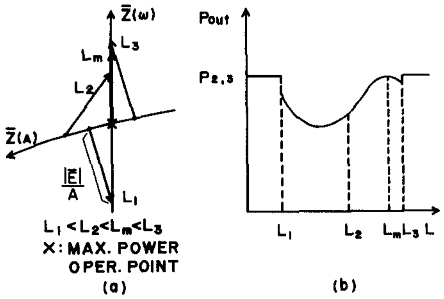

Fig. 2. (a) An impedance diagram explaining the effects of the resonator cavity tuning. (b) The power generated by the active device versus the value of inductance L, where the change in L represents the cavity tuning effect.

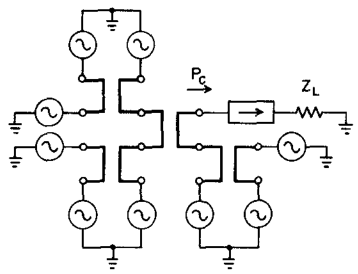

Fig. 3. A 9-oscillator corporate structure.

symbol represents the short-slot coupler shown in Fig. 1(b) in the present work, but other types of couplers, such as the 3-dB strip-line coupler, can be used as well. Referring to Fig. 1(a), we let oscillator 1 generate power P_1 at a frequency f_1. P_1 is equally divided and injected into oscillators 2 and 3. Operation of oscillators 2 and 3 under a high-level injection signal can be explained using the impedance diagram shown in Fig. 2(a) according to Kurokawa [7], where $-\bar{Z}(A)$, $\bar{Z}(\omega)$, and $\bar{E}$ represent the device impedance, circuit impedance, and injection signal, respectively, and A is the amplitude of oscillation current in the device. We assume here that the oscillators are designed to generate the maximum power under free-running conditions, as implied by the location of the maximum-power operating point (× mark), and that the device line is slightly slanted. Now suppose that one tunes the oscillator cavity to vary the value of inductance L while keeping the frequency f_1 and intensity $|\bar{E}|$ of the injection signal constant. As L increases, the circuit impedance locus shifts upwards and the impedance diagram changes as shown in Fig. 2(a). Frequency locking takes place at L values between L_1 and L_3. The power generated by the device varies as shown in Fig. 2(b), taking the maximum value of P_2 (P_3) which is equal to the output power under free-running conditions at L_m. When $L=L_m$, the injection signal impedance bridging between $\bar{Z}(A)$ and $\bar{Z}(\omega)$ is purely reactive and the net power transferred from the locking source to the locked oscillator is zero. Thus the locked oscillators 2 and 3 generate P_2 and P_3 and reflect all the locking-signal power, $P_1/2$ and $P_1/2$, simultaneously, when they are detuned properly.

When the oscillators 2 and 3 are adjusted for the maximum power, the relationship

$$a_3 = ja_2 \tag{1}$$

is automatically satisfied because the injection signals of equal magnitude into the identical oscillators have a 90° phase difference, where a_k and b_k ($k=1,2,3,4$) are the power waves going into and out the coupler at ports 1 through 4, respectively. Under the condition of (1), one has

$$b_1 = 0 \tag{2}$$

$$b_4 = j\sqrt{2a_2}\,\exp j\theta = \sqrt{2a_3}\,\exp j\theta \tag{3}$$

where θ is the phase shift between ports 1 and 2 (3 and 4). Hence, the power injected back into oscillator 1 is zero, while the output power P_c is given by

$$\begin{aligned} P_c &= |b_4|^2 = 2|a_2|^2 = 2|a_3|^2 \\ &= 2P_2 + P_1 = 2P_3 + P_1 \\ &= P_1 + P_2 + P_3 \end{aligned} \tag{4}$$

indicating that the sum of the maximum power is delivered to the matched load. It is perhaps worth mentioning that the high-level injection from the locking oscillator 1 into the locked oscillators 2 and 3 with no (in practice, small) reverse injection improves the stability of the circuit operation over that of the conventional 2-oscillator combining circuit.

The above principles can be extended to a larger number of oscillators. If we replace all the oscillators in Fig. 1(a) with three of the 3-oscillator structures, we obtain a 9-oscillator corporate structure shown in Fig. 3. In principle, it is possible to form a corporate structure in which 3^N

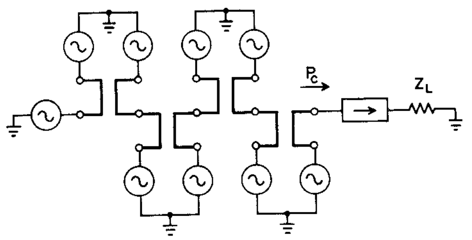

Fig. 4. A 9-oscillator tandem structure.

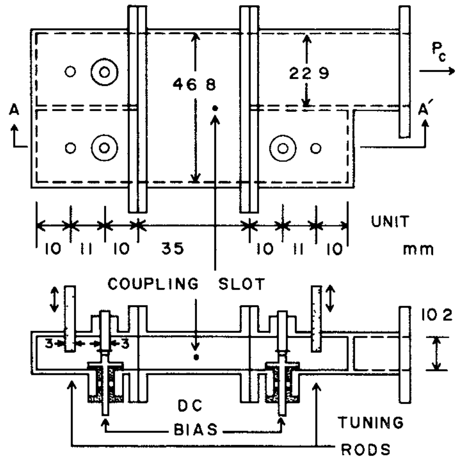

Fig. 5. Construction of an experimental 3-oscillator structure using post-mount Gunn oscillators and a short-slot coupler.

oscillators are combined with $(3^N-1)/2$ couplers in this way. Another possibility is to replace oscillator 1 alone with the 3-oscillator structure. In this way, it is possible to form a tandem structure in which $2N+1$ oscillators are combined with N couplers. A $2\times4+1=9$-oscillator tandem structure is shown in Fig. 4.

Experiments

Experimental power combining structures were built using a standard rectangular waveguide (22.9 mm × 10.2 mm) and X-band Gunn diodes (NEC GD-511AA, 15–30 mW).

Fig. 5 illustrates the construction of an experimental 3-oscillator structure, where the coupling slot is 35 mm long and the oscillators are of the post-mount type having a dielectric rod for tuning. The oscillator section and the coupling section are joined by the flanges to allow direct access to the individual oscillators for measurements. The 3-oscillator structure can be adjusted for a maximum output power at a prescribed frequency f_c by the following steps: 1) Operate oscillator 1 alone and tune f_1 to a frequency slightly (5–10 MHz) above f_c. 2) Operate all the oscillators and adjust the tuning rods of oscillators 2 and 3 repeatedly for maximum power at f_c. 3) Tune oscillator 1 to see whether the combined output power becomes maximum at f_c. If it does, terminate the adjustment. 4) If not, tune oscillator 1 to bring the combined-oscillation frequency closer to f_c and repeat the above steps 1)–3).

Typical results of such circuit adjustments in which f_c

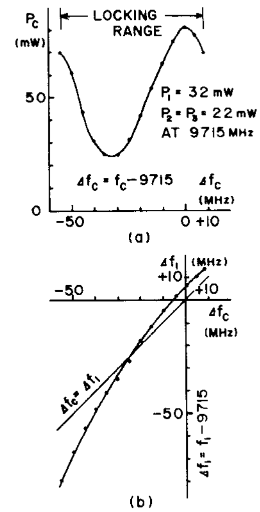

Fig. 6. Typical tuning characteristics of the 3-oscillator structure. The circuit was adjusted for the maximum output power at 9715 MHz and oscillator 1 alone was tuned. (a) The output power versus oscillation frequency over the locking range. (b) The oscillation frequency of the combined circuit f_c versus free-running oscillation frequency of oscillator 1, f_1.

TABLE I
Results of Power-Combining Experiments at $f_c=9733$ MHz Using the Structure of Fig. 5

	Free Running						Combined	
	Freq. Deviation (MHz)			Power (mW)			Power (mW)	Eff (%)
No.	Δf_1	Δf_2	Δf_3	P_1	P_2	P_3	P_c	η
1	+11	−19	−13	21.0	28.0	25.5	73.0	98
2	+10	−22	−16	19.0	18.0	19.0	58.0	103
3	+11	−23	−18	22.5	22.5	17.5	63.0	101
4	+14	−24	−16	21.0	28.0	23.5	72.0	99
5	+9	−18	−16	24.7	23.3	23.1	72.0	101

was set at 9733 MHz are summarized in Table I, where P_c is the combined power given in milliwatts. The output power and oscillation frequencies of the individual oscillators are given in the P_1, P_2, P_3, Δf_1, Δf_2, and Δf_3 columns, where $\Delta f_i = f_i - f_c (i=1,2,3)$. The measurements were taken on the individual oscillators after disassembling the optimally adjusted circuit of the flanges while leaving the oscillator tunings and dc bias untouched. The power-combining efficiency η defined by

$$\eta = \frac{P_c}{P_1+P_2+P_3} \times 100 \text{ (percent)} \tag{5}$$

is also given. In all the cases, the power-combining efficiency of about 100 percent was obtained.

Typical tuning characteristics of the 3-oscillator structure are shown in Fig. 6, where the circuit was first adjusted for the maximum power at 9715 MHz and then oscillator 1 alone was tuned. The circuit remained mutually frequency locked over a range of Δf_c from −55 to +8 MHz, where $\Delta f_c = f_c - 9715$ MHz. The output power varied over the locking range as shown in Fig. 6(a). Measured relationship between Δf_c and Δf_1 is shown in Fig. 6(b), where $\Delta f_1 = f_1 - 9715$ MHz. The deviation of the

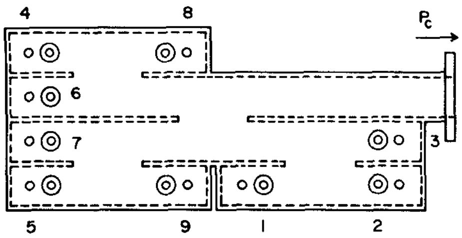

Fig. 7. An experimental 9-oscillator corporate structure.

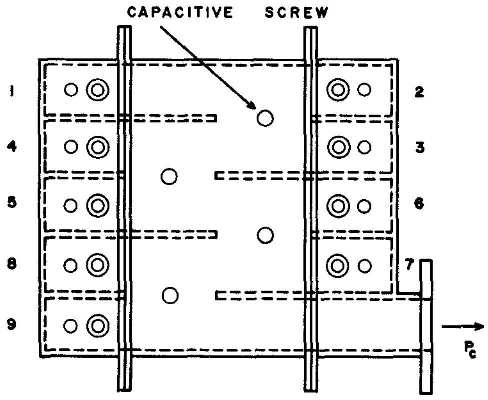

Fig. 8. An experimental 9-oscillator tandem structure.

Δf_c versus Δf_1 curve from the $\Delta f_c = \Delta f_1$ straight line reflects the presence of reverse injection into oscillator 1.

Experimental 9-oscillator corporate and 9-oscillator tandem structures we have built are illustrated in Figs. 7 and 8, where the oscillator construction is identical to that shown in Fig. 5 and the coupler design is the same, i.e., the iris measures 10.2 mm×35 mm, for all stages. We have also built a 13-oscillator tandem structure of similar construction. The capacitive screws to provide the correct 90° phase shift were found necessary for the couplers in the multistage tandem structure. The use of matched-pair diodes for each stage of the multistage tandem structure was also found necessary to make the circuit operation predictable, in particular, during circuit adjustment, thereby to achieve a high power-combining efficiency.

The circuit adjustment can be made by tuning the oscillators in turn suggested by the numbers assigned to them in Figs. 7 and 8. The adjustment requires iteration. Results of power-combining experiments are presented in Fig. 9, where the combined power P_c, given in milliwatts, is plotted along the ordinate and the sum of the output power from the individual oscillators along the abscissa. In Fig. 9 the crosses represent results obtained with the corporate structure, the circle and triangle, results obtained with the 9- and 13-oscillator tandem structures, respectively. The corporate structure can efficiently combine the output power from 3, 5, and 7, as well as from 9 oscillators, as indicated by the numbers of the oscillators in operation. Power-combining efficiencies of 92.4 percent at 9610 MHz, 95.3 percent at 9620 MHz, and 92.6 percent at 9607 MHz were obtained with the 9-oscillator corporate and 9- and 13-oscillator tandem structures, respectively. The output power from the individual oscillators of the 13-oscillator tandem structure into the same waveguide load at 9607 MHz under free-running conditions is listed in Table II along with their frequency deviations given in megahertz, $\Delta f_i = f_i - f_c$, where f_i is the free-running oscillation frequencies and $f_c = 9607$ MHz. Table II shows that the frequency deviation, which represents the degree of detuning, increases as the number of stages increases. This is to be expected, because the magnitude of the injection-signal vector in Fig. 2(a), $|\bar{E}|/A$, increases as the injection signal level increases, and a larger frequency deviation is required for the higher order oscillators to bring the device operating point to the maximum power point.

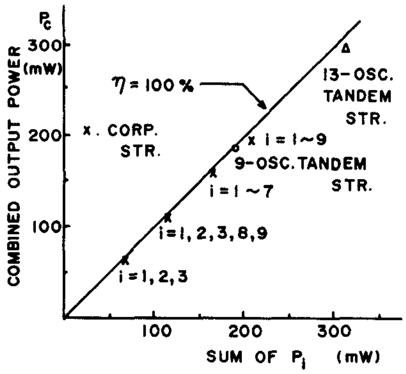

Fig. 9. Results of power-combining experiments obtained with the 9-oscillator corporate, 9- and 13-oscillator tandem structures. ×: corporate structure, where the oscillators in operation are indicated by the oscillator numbers. O: 9-oscillator tandem structure. △: 13-oscillator tandem structure.

TABLE II
FREE-RUNNING OSCILLATION FREQUENCIES AND OUTPUT POWER OF INDIVIDUAL OSCILLATORS IN THE 13-OSCILLATOR TANDEM STRUCTURE

Stage	Osc No.	Δf_i (MHz)	P_i (mW)
	1	0	22
1	2	−16	16
	3	−20	25
2	4	−24	23
	5	−24	21
3	6	−34	16
	7	−26	21
4	8	−32	28
	9	−32	27
5	10	−36	27
	11	−40	26
6	12	−40	30
	13	−40	31
	Sum of P_i = 313		

$\Delta f_i = f_i - f_c$
f_c = 9607 MHz, P_c = 290.6 mW,
η = 290.6/313 = 0.928

The power-combining efficiency of the combining networks of the 3^N-corporate and $2N+1$-tandem structures is estimated for an assumed loss of −0.1 dB per pass (loss measured at 9.6 GHz was −0.033 dB per pass), and the results are represented by the solid curves in Fig. 10, where the number of oscillators combined is plotted along the abscissa. The broken curves in Fig. 10 are the similar plots for the 2^N-corporate structure, the chain-combining

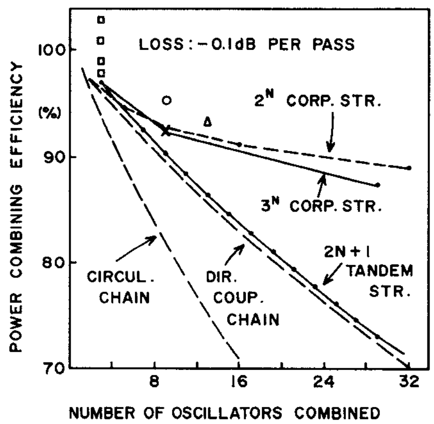

Fig. 10. The power-combining efficiency versus the number of oscillators combined for various combining networks. Solid curves: 3^N-corporate and $2N+1$-tandem structures. Broken curves: 2^N-corporate structure, the chain-combining structures using directional couplers and circulators. A loss of -0.1 dB per pass is assumed for all the curves.

structures using directional couplers and circulators, all assuming -0.1 dB per pass, for comparison. The experimental results obtained with the 3-oscillator, 9-oscillator corporate, 9- and 13-oscillator tandem structures are represented by the boxes, cross, circle, and triangle, respectively.

All these circuits readily generate the combined power upon applying the dc bias with no need for readjustment once they are adjusted. The stability of operation of the tandem structures including 3-oscillator structure may be stated as good or fair. This is because the injection signal levels are high in the tandem structures. But, the stability of operation of the 9-oscillator corporate structure may become marginal when the injection signals into oscillators 8 and 9, referring to Fig. 7, are made too weak.

Conclusions

A method of combining power from 3, 3^N, and $2N+1$ oscillators has been developed using short-slot couplers in conjunction with high-level injection locking. The principles of the method were supported by the experiments using 3-oscillator, 9-oscillator corporate, 9- and 13-oscillator tandem structures having X-band Gunn diodes, demonstrating power-combining efficiencies of about 100, 92, 95, and 93 percent, respectively, at 9.6–9.7 GHz. The method appears to be applicable to all types of oscillators, including solid-state oscillators and electron-tube oscillators. Of particular interest for future works is the combination of the present method and the single-cavity-multiple-device techniques for it could extend the total number of devices combined to a 100–300 range. Further experiments are planned and, in part, currently under way on application of the method to IMPATT, millimeter-wave, and single-cavity-multiple-device oscillators.

Acknowledgment

The authors would like to thank K. Sekido and S. Agu of Nippon Electric Company for supplying the diodes used in the experiments.

References

[1] C. T. Rucker, "A multiple-diode high-average power avalanche-diode oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, p. 1156, Dec. 1969.
[2] K. Kurokawa and F. M. Magalhaes, "An X-band 10-watt multi ple-IMPATT oscillator," *Proc. IEEE*, vol. 59, p. 102, Jan. 1971.
[3] R. S. Harp and H. L. Stover, "Power combining of X-band IMPATT circuit modules," presented at the 1973 IEEE Int. Solid-State Circuits Conf., Feb. 1973.
[4] H. Fukui, "Frequency locking and modulation of microwave silicon avalanche diode oscillators," *Proc. IEEE*, vol. 54, p. !475, Oct. 1966.
[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] W. O. Schlosser and A. L. Stillwell, "A traveling-wave approach to high-power solid-state oscillator," *Proc. IEEE*, vol. 56, p. 1588, Sept. 1968.
[7] K. Kurokawa, "Injection locking of microwave solid-state oscillators," *Proc. IEEE*, vol. 61, p. 1368, Oct. 1973.
[8] M. Nakajima, "A proposed multistage microwave power combiner," *Proc. IEEE*, vol. 61, p. 242, Feb. 1973.
[9] K. J. Russell, "Microwave power combining techniques," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, p. 472, May 1979.
[10] H. J. Riblet, "The short-slot hybrid junction," *Proc. IRE*, vol. 40, p. 180, Feb. 1952.