Crucial Factors in Power Combining by Oversized Cylindrical Cavity Multiple-Device Structures

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Abstract —Power combining in oversized cylindrical cavities has hiterto not given successful results. The purpose of this paper is to show both analytically and experimentally that the combining efficiency in such cavities can be remarkably improved by finding the optimum position and number of devices. An "equivalent loss resistance," which indicates the cavity loss per device when every device generates its available power, is introduced, and the number and position of devices which minimize the quantity is obtained for a TM_{0n0}-mode cavity by carrying out FEM field analysis. Power-combining experiments using TM_{020}- and TM_{030}-mode cavities confirmed the theory and achieved excellent power-combining efficiencies of, respectively, 117 percent and 107 percent in the TM_{020}-mode cavity with ten devices and in the TM_{030}-mode one with 12 devices.

I. Introduction

RECENTLY, a number of microwave and millimeter-wave power combining techniques have been proposed to meet the demand for high-power solid-state sources [1], [2]. Among them, cylindrical cavity combiners are beneficial because of their simple structure, small size, and easy fabrication [3]–[11]. The power-combining scheme using cylindrical cavities with TM_{0n0} modes can be classified into two types depending on the output structure: one is the "central loading" type, having an output probe at the cavity center; the other is the "peripheral loading" type, having an output window at a certain position on the sidewall of the cavity. In the case of cavities of lower modes, such as the TM_{010} and the TM_{020} mode, good performance has been reported for the two types. However, the oversized cavities such as the TM_{030}- and the TM_{040}-mode, have so far not given successful results [1], [4], [11]. In oversized cavities, the peripheral loading type causes noticeable disturbance to the symmetry of the electromagnetic field, which makes it difficult for each device to generate its available power simultaneously [13]. Therefore, in the following the discussion of efficient power combining using oversized cavities is confined to the central loading case.

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It is understood that unsuccessful results in conventional oversized cavity combiners are due to an increase of power loss at the wall of the large cavity. The cavity loss decreases with the stored energy of the cavity. Strong coupling of each device to the electromagnetic field is required in order to lower the stored energy when each device generates its available power. Furthermore, for discussing the power-combining efficiency, a quantity which indicates the cavity loss per device must be introduced. This quantity is referred to as the equivalent loss resistance in the following.

This paper aims to attain high combining efficiencies in oversized cavities by minimizing the equivalent loss resistance. In Section II, we give definitions of the "device–field coupling" and the equivalent loss resistance and discuss the relation of these quantities to the combining efficiency. Section III is devoted to the calculation of the electromagnetic field in TM_{0n0}-mode multiple-device cylindrical cavities using finite-element analysis in order to obtain the magnitudes of the quantities defined above and to determine the optimum device positions and number of devices. Finally, we give the results of a power-combining experiment using TM_{020}- and TM_{030}-mode cavities to confirm the theory.

II. Relation of Device–Field Coupling and Equivalent Loss Resistance to Power-Combining Efficiency

Suppose that N active devices with the same characteristics are mounted in a power combiner cavity. When each device generates its available power P_d, the output power of the combiner, $P_{o,\max}$, can be written as

$$P_{o,\max} = NP_d - P_{\text{loss}} \tag{1}$$

where P_{loss} is the power loss at the cavity wall. In a cavity of sufficiently low and fixed height, the internal Q of the cavity, Q_0, is almost constant regardless of the cavity modes, and the power loss at the cavity wall is in proportion to the energy stored in the cavity.

Denoting the amplitude of the RF device current and the energy stored in the cavity when each device generates

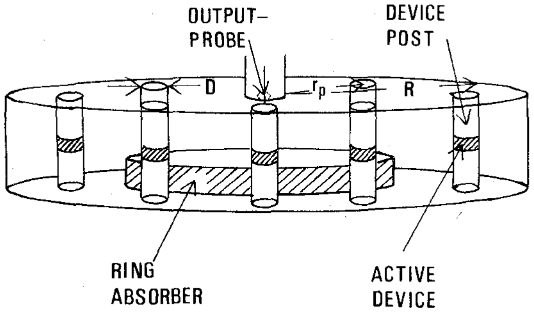

Fig. 1. Cylindrical cavity power combiner.

its available power as I_{opt} and W_{op}, respectively, let us define the degree of device–field coupling κ as [14]

$$\kappa = I_{\mathrm{opt}}/\sqrt{W_{op}}. \tag{2}$$

Then, P_{loss} is expressed as

$$P_{\mathrm{loss}} = \frac{\omega_0}{Q_0} W_{op} = \frac{\omega_0 I_{\mathrm{opt}}^2}{\kappa^2 Q_0} \tag{3}$$

where ω_0 is the resonant frequency of the cavity. The power loss can be minimized by making device–field coupling as strong as possible.

The combining efficiency, η, is defined theoretically as

$$\eta = P_{o,\max}/(NP_d) \tag{4}$$

which, using (1) and (3), gives

$$\eta = 1 - \gamma \frac{I_{\mathrm{opt}}^2}{P_d} \tag{5}$$

where

$$\gamma = \frac{\omega_0}{\kappa^2 N Q_0}. \tag{6}$$

The term *equivalent loss resistance* is used for γ because $\gamma I_{\mathrm{opt}}^2$ represents the cavity wall loss per device.

Equation (5) shows that the combining efficiency increases with decreasing γ. The maximum combining efficiency can thus be attained by finding the device positions and the number of devices which minimize γ. Note that the quantity γ serves as a universal measure for comparing combining efficiencies between various multiple-device cavities.

Excellent correlation between theory and experiment was confirmed using a double-device oscillator of the waveguide cavity type, which is a prototype of a multiple-device oscillator [15].

III. Cylindrical Cavity Structure for Efficient Power Combining

Consider the cylindrical cavity multiple-device structure shown in Fig. 1, where many device posts are placed with uniform spacing on the circle of radius r_p in a low cylindrical cavity. The output power is taken from the output probe at the center of the cavity through the coaxial line. Because the device locations have axial symmetry with respect to the output probe, every active device can operate perfectly in the same manner when it couples to the electromagnetic field of the TM_{0n0} mode. Microwave absorbers are located at the positions of vanishing electric field of the desired TM_{0n0} mode for the purpose of suppressing undesired modes.

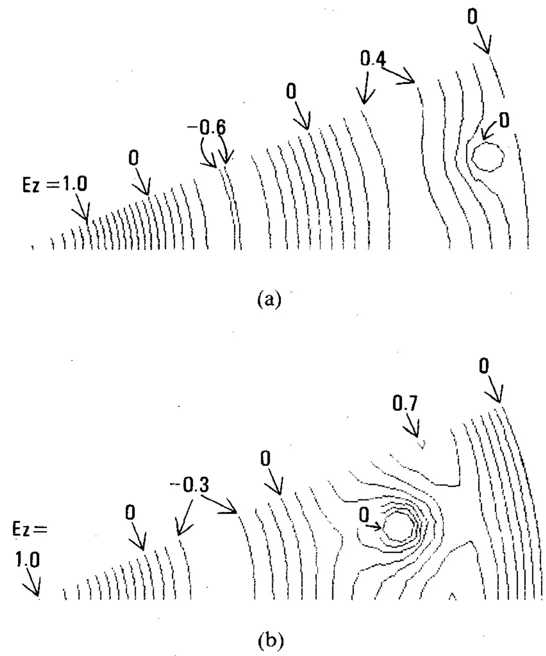

Fig. 2. Electric field contour maps for TM_{030}-mode cavities with 12 device posts. Same stored energies are given in both cavities. (a) $R = 48.0$; $r_p = 45.0$. (b) $R = 48.0$; $r_p = 36.0$. (b) corresponds to the case of maximum κ when the same energies are stored. (E_z is the electric field along the cavity axis. All dimensions are in millimeters.)

A. Field Distribution and κ

The electromagnetic fields in the multiple-device cylindrical cavities can be obtained numerically using the finite-element method. The device posts are replaced by conductor posts. Typical results of the electric fields in TM_{030}-mode cavities are shown in Fig. 2: (a) is for the case where the device posts are placed near the cavity wall, while (b) is for the case where the device posts are moved toward the maximum electric field which appears in the case of no device posts. The distributions of the electric fields when the same energy is stored in both cavities are given. Comparing case (b) with case (a), the contours of the electric field are more dense around the post in (b), which results in a stronger magnetic field surrounding the post and accordingly in a larger amplitude of the RF device current in (b). Since κ is proportional to the device current in a cavity with a certain fixed stored energy, case (b) is preferable.

B. Dependence on Device Position and Number of Devices

The values of κ and γ are calculated and shown in Fig. 2 as a function of the distance from the cavity center to a device post, r_p, with the number of devices as a parameter for TM_{020}-, TM_{030}-, and TM_{040}-mode cavities. Because R and D are fixed in this calculation, the resonant frequency of the cavity varies within about 30 percent with r/R.

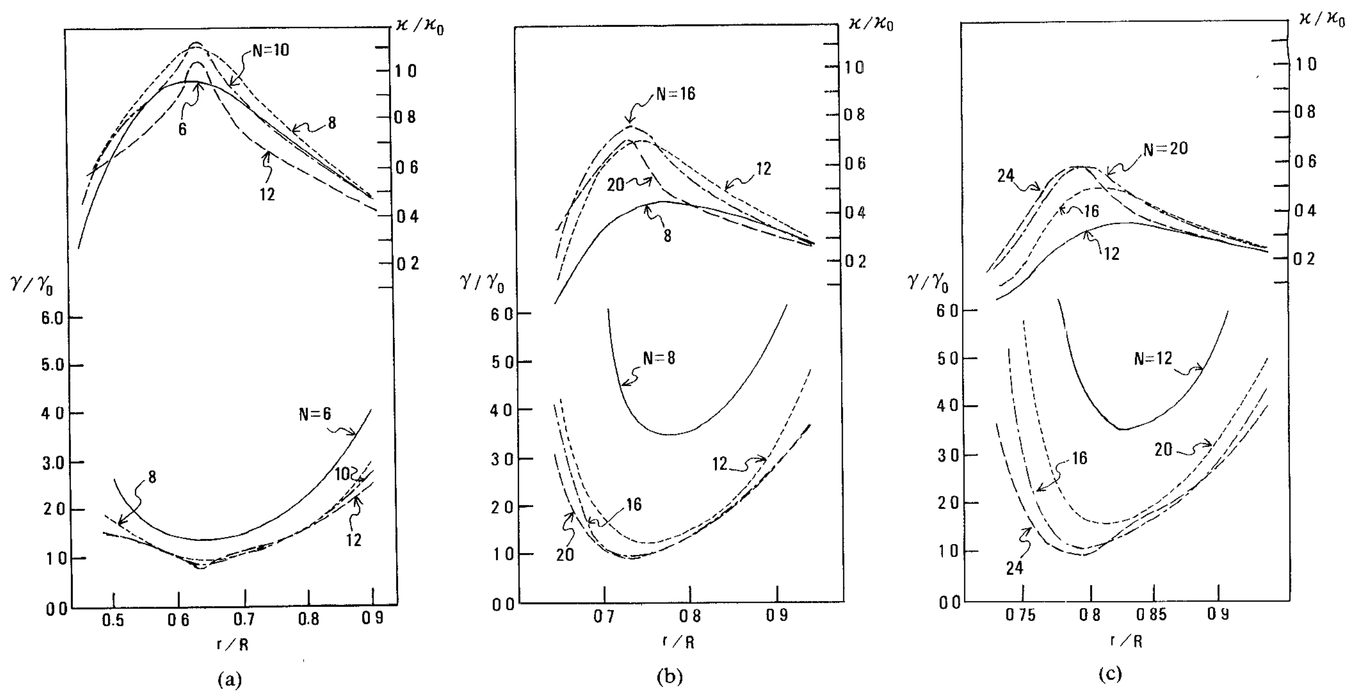

Fig. 3. Dependence of κ and γ on device position ($D = 3.0$). (a) TM_{020} mode ($R = 30.0$). (b) TM_{030} mode ($R = 48.0$). (c) TM_{040} mode ($R = 64.0$).

However, even in the calculation on the cavities with constant resonant frequency, the values of κ and γ deviate only slightly from Fig. 3.[1] It is seen from Fig. 3 that, as the order number of the TM_{0n0} mode, n, increases, i) the maximum value of κ gradually decreases and ii) the number of device posts minimizing γ increases. It is also noticed that, for each combining mode, the peak value of κ decreases with increasing N after reaching the maximum. This is interpreted as follows. Increasing the number of device posts causes a narrowing of adjacent intervals, which prevents the field from surrounding the device post and causes κ to decrease. The decrease of κ in turn causes an increase in cavity loss. However, the cavity loss per device, and accordingly γ, are considered to be almost constant. Calculation of profiles of the electric field in a TM_{0n0}-mode cavity showed that the device position giving maximum κ is a little outside of the position of maximum electric field which appears in the cavity with no device posts and the same resonant frequency.

IV. Experiment

A power-combining experiment was carried out in TM_{020}- and TM_{030}-mode cylindrical cavity structures as shown in Fig. 4. Gunn diodes (GD511A, manufactured by the Nippon Electric Company, NEC) were used and located uniformly on the circle with radius r_p about the cavity center. The combined output power taken from the output probe at the cavity center is fed to the waveguide through the coaxial–waveguide converter. The depth of the probe can be varied to adjust the output coupling of the cavity. The multiple-device cavities used in the experiment and the values of the parameters κ and γ are given in Table I. The radius of each cavity, R, is determined in order to tune the desired mode frequency near 9.0 GHz. In cavities #1 and #4 the devices are located near the cavity wall, while in cavities #2, #3, and #5 they are located at the optimum positions which minimize γ and are specified in Fig. 3. The frequencies of the relevant undesired modes calculated by the finite-element analysis are shown in Table II. To suppress these undesired modes, the microwave absorber rings of thickness 0.15 mm and height 2 ~ 4 mm are placed at the positions of vanishing electric field of the desired TM_{0n0} mode. Measurement of the

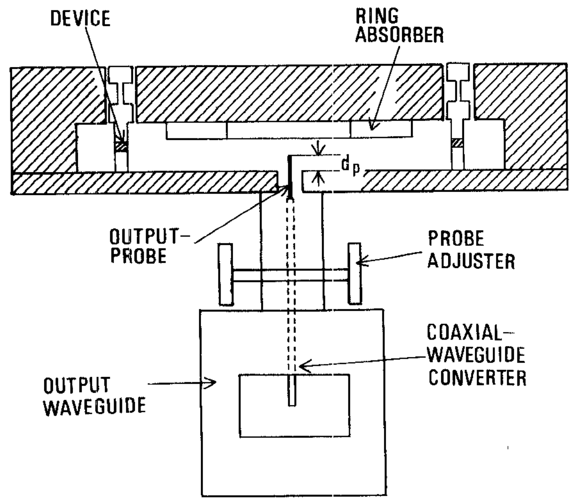

Fig. 4. Structure of probe-output multiple-device cylindrical cavity.

[1]Multiple-device cavities with the same r_p/R, D/R, and N have κ and γ of the same magnitudes. Accordingly, the calculation of κ and γ under constant resonant frequency with D and r_p/R fixed can be replaced by the calculation in which D is varied with R and r_p fixed. The result shows that κ varies within 8 percent for the maximum variation of 30 percent of D.

TABLE I
MULTIPLE-DEVICE CAVITIES USED FOR EXPERIMENT AND THEIR κ AND γ VALUES

Cavity No.	Mode	N	R(mm)	r(mm)	oscillation freq. (GHz)	κ/κ_0	γ/γ_0
#1	TM_{020}	8	30.1	27.5	9.29	0.463	0.33
#2		8	37.7	23.9	9.03	1.022	0.98
#3		10	39.0	25.0	9.52	1.000	1.00
#4	TM_{030}	12	47.6	45.1	8.95	0.303	4.80
#5		12	52.0	40.0	9.31	0.654	1.25

TABLE II
RESONANT MODES AND THEIR FREQUENCIES IN GHz

Cavity No.	undesired			desired	undesired		
#1			TM_{210} 8.63	TM_{020} 9.27	TM_{310} 10.68		
#2			TM_{210} 8.72	TM_{020} 8.93	TM_{310} 9.70		
#3			TM_{210} 8.94	TM_{020} 9.16	TM_{120} 9.88	TM_{310} 10.15	
#4		TM_{410} 7.97	TM_{220} 8.85	TM_{030} 9.08	TM_{510} 9.23	TM_{610} 10.27	TM_{320} 10.29
#5	TM_{410} 8.36	TM_{220} 9.20	TM_{510} 9.22	TM_{030} 9.39	TM_{610} 9.54	TM_{320} 10.14	

internal Q of the cavities with and without microwave absorbers was carried out and showed that the loss due to microwave absorbers was quite small: about one fifth as large as the wall loss.

Fig. 5 shows the relative combining efficiency versus output probe depth for the TM_{020}- and TM_{030}-mode combiners, respectively, where the relative combining efficiency is defined by the ratio of the output power to the sum of all the maximum output powers of each device tested in a conventional single-device waveguide cavity (NEC LD4030). The TM_{020}-mode octuple-device cavity (cavity #2) in which the devices are located at the optimum positions is greater in relative combining efficiency than the cavity (cavity #1) which has devices near the cavity wall. But in cavity #2, once mode jump takes place into an undesired mode, the TM_{210} mode, a return to the desired mode never occurs unless the dc power is turned on again. Then, the decuple-device cavity (cavity #3) was examined. This cavity was expected to be effective for the suppression of the TM_{210} mode because in this cavity device–field coupling varies among the devices for the TM_{210} mode, and the stability of this mode is reduced in comparison with the case of the octuple-device cavity (cavity #2). In the power-combining experiment using cavity #3 with the same microwave absorbers as used in cavity #2, stable desired mode operation became possible, and high combining efficiency, up to 117 percent, was achieved.

Next, the TM_{030}-mode cavity (cavity #5) with optimum device position attained a relatively high combining efficiency, amounting to 107 percent, while the cavity with devices near the cavity wall (cavity #4) gave no more than 87.6 percent. These experiments show that, in maximum output power operation, the depth of the output probe of the cavity with optimum device position is greater than that of the cavity with devices near the cavity wall. This can be explained by the fact that, in the former, the

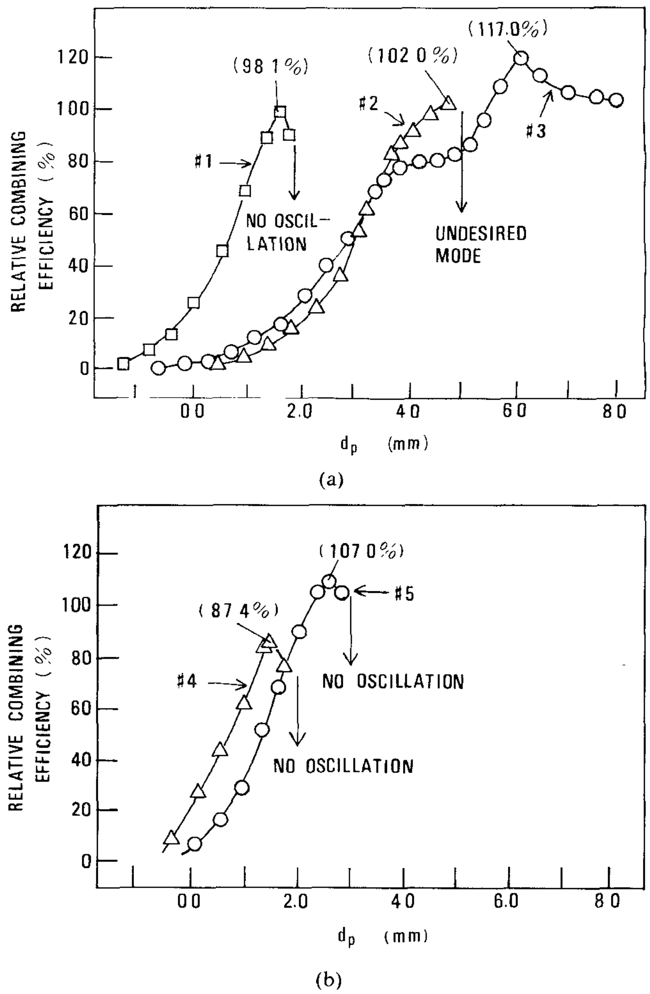

Fig. 5. Relative combining efficiency versus probe depth d_p. (a) TM_{020}-mode combiners. (b) TM_{030}-mode combiners.

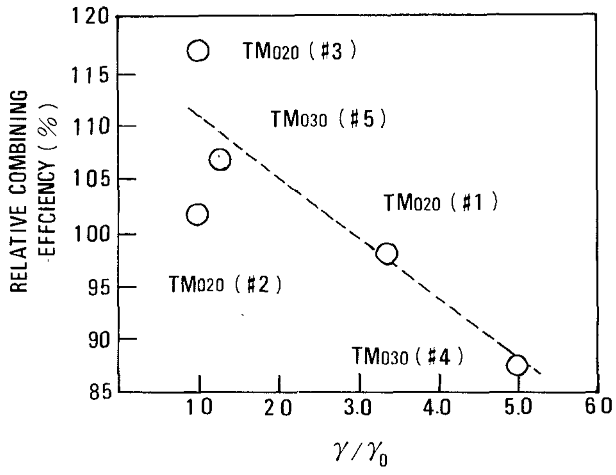

Fig. 6. Relative combining efficiency versus γ for the combiners used in the experiment.

electric field at the cavity center is weaker because of smaller stored energy, so a deeper output probe is required than in the latter. In other words, the coupling between the cavity and output coaxial line becomes strong by taking optimum device positioning. The dependence of the relative combining efficiency on γ is plotted in Fig. 6. It is seen that the smaller γ is, the higher the relative combining efficiency, in accordance with the prediction of (5) in Section II. The deviation of relative combining efficiencies in cavities, #2, #3, and #5 from the linear relation η and γ is thought to be due to the difference in absorbers used for undesired mode suppression.

V. Conclusion

For discussion of the power-combining efficiency in cylindrical cavity multiple-device oscillators, the "equivalent loss resistance," which indicates the cavity loss per device when every device generates its available power, has been introduced, and the number and position of devices which minimize the quantity have been obtained by carrying out field analysis by the finite-element method. The theoretical considerations and analytical predictions have been successfully confirmed by the experiments, in which excellent combining efficiency has been achieved. The technique of optimum device allocation developed in this paper can also be applied to the passive cavity combiners used in high-power solid-state amplifiers including power dividing and combining stages.

In TM_{020}- and TM_{030}-mode power combining, treated in this paper, the power loss by microwave absorbers was less than that by the cavity wall. However, it is supposed that, in power combining using the TM_{040} mode and higher modes, the power dissipation in absorbers rises due to the increased number of undesired modes. Efficient suppression of undesired modes takes on added importance in the further development of oversized cavity power combiners. Effective power combining in higher TM_{m10}-mode cavities with output windows is another interesting subject for investigation.

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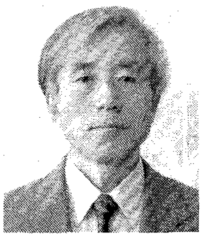

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