Techniques for Increasing the Bandwidth of a TM_{010}-Mode Power Combiner

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***Abstract*—A computer analysis of the TM_{010}-mode power combiner for N diodes is described which identifies circuit parameters that increase the bandwidth of the power combiner. These parameters reduce the external Q and provide unique techniques for increasing the bandwidth of injection-locked power combiners. Comparisons with external Q measurements give experimental verification of the analysis.**

I. Introduction

The TM_{010}-MODE cylindrical power combiner is inherently narrow-band as an amplifier and has a narrow injection-lock bandwidth when operated as an oscillator because of its high Q resonant structure and high external Q, Q_{ext}. Because of its excellent mode separation, ± 5 GHz at X band, it has been successfully used to combine up to 16 IMPATT's [1], [2]. It does not require mode suppression filters and has achieved higher power levels than the broader bandwidth radial line power combiner.

In this paper, methods are described that can be used to increase the bandwidth of the TM_{010}-mode power combiner while maintaining high power levels. The parameters considered in the analysis and measurement are the coupling between the external circuit and resonator, the coupling of the IMPATT module to the resonator, the number N of diodes combined, and the characteristic conductance of the external circuit being fed by the power combiner.

II. Analysis of a TM_{010}-Mode Cavity Power Combiner

A cylindrical TM_{010}-mode power combiner consisting of N symmetrically placed IMPATT loaded coaxial circuits, coupled to the magnetic field near the periphery of the resonator cavity, coherently adds the power of each diode P_d with a combining efficiency η_c such that the power output P_o is

$$P_o = \eta_c N P_d. \tag{1}$$

The equivalent circuit, based upon Kurokawa's original analysis [3], [4] in Fig. 1, has the condition for oscillation that

$$-Z_g \equiv -R_g - jX_g = Z_d \equiv R_d + jX_d. \tag{2}$$

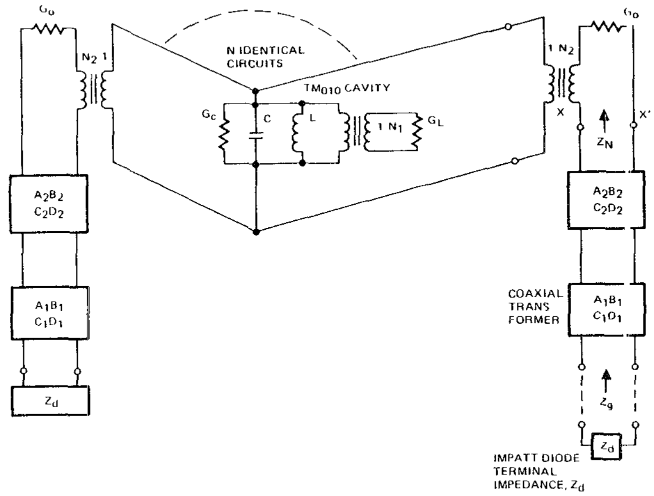

Fig. 1. The power combiner equivalent circuit.

Kramer [5] has shown that, when $R_d \neq -R_g$, the power P_d differs from its maximum value $P_{d\max}$ by a value

$$P_d = \frac{G_g(2G_{opt} - G_g)}{G_{opt}^2} P_{d\max} \tag{3}$$

where

$$G_{opt} = \frac{-R_d}{R_d^2 + X_d^2} \tag{4}$$

and

$$G_g = \frac{R_g}{R_g^2 + X_g^2}. \tag{5}$$

The circuit giving an appropriate match to the IMPATT, consisting of a two-step transformer, represented by the $ABCD$ matrix in Fig. 1, yields Z_g from Z_n by successive iterations of a lossless transmission line equation as follows:

$$Z_g = \frac{A_1 Z' + B_1}{C_1 Z' + D_1} \tag{6}$$

where

$$Z' = \frac{A_2 Z_N + B_2}{C_2 Z_N + D_2}$$

and where A_i, B_i, C_i, and D_i, for $i = 1,2$, are the transformer $ABCD$ parameters, and Z_N appears across terminals x–x'.

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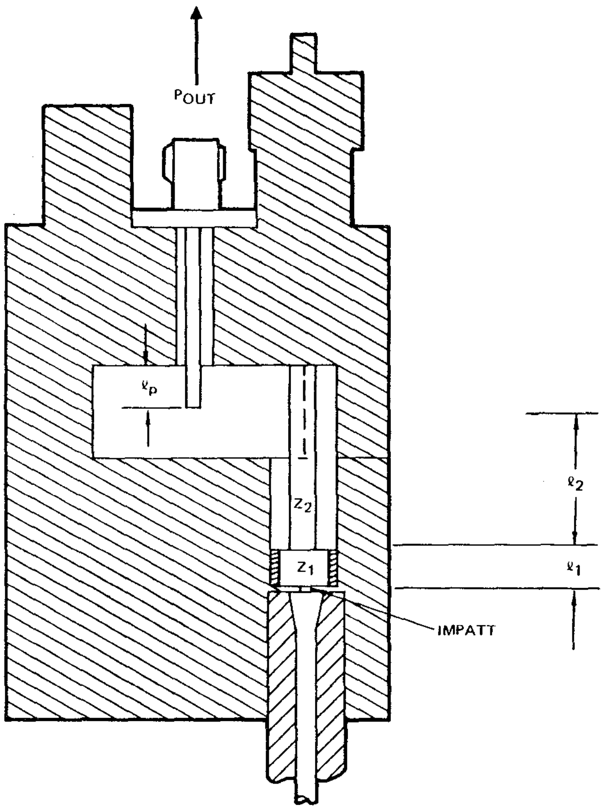

Fig. 2. The power combiner dimensions.

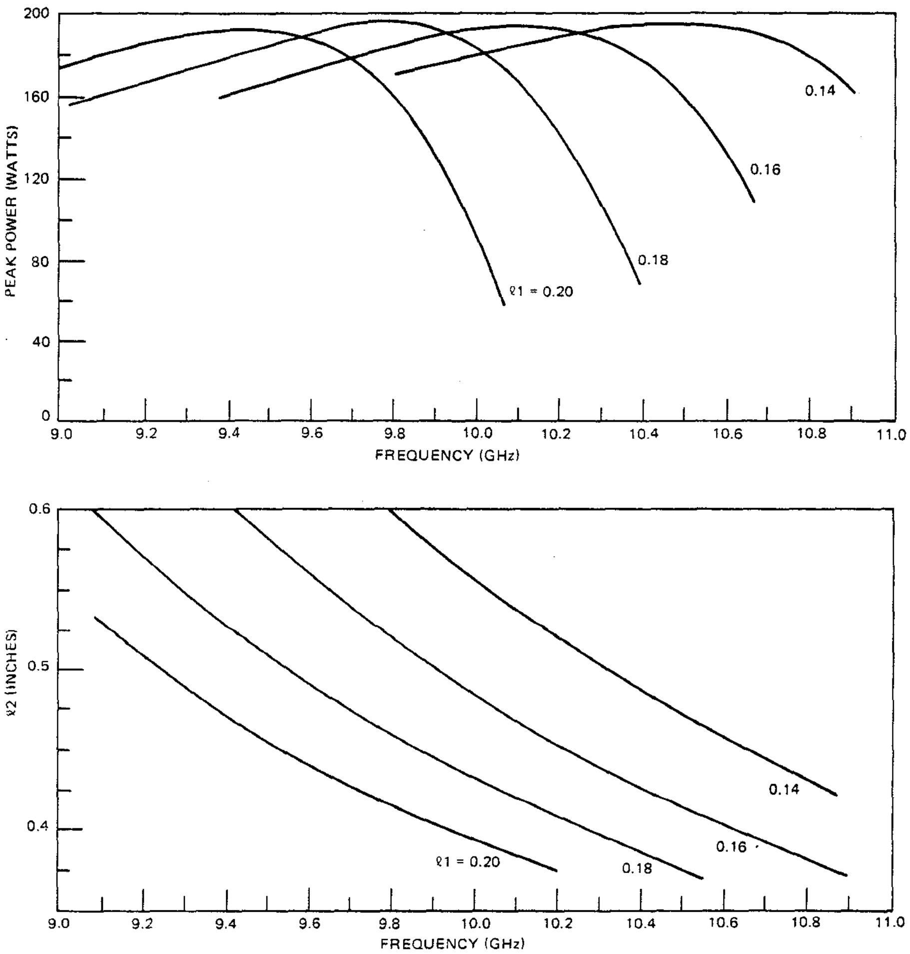

Fig. 3. The calculated power and tunability for a 16-diode power combiner having $Z_1 = 20\ \Omega$ and $Z_2 = 50\ \Omega$.

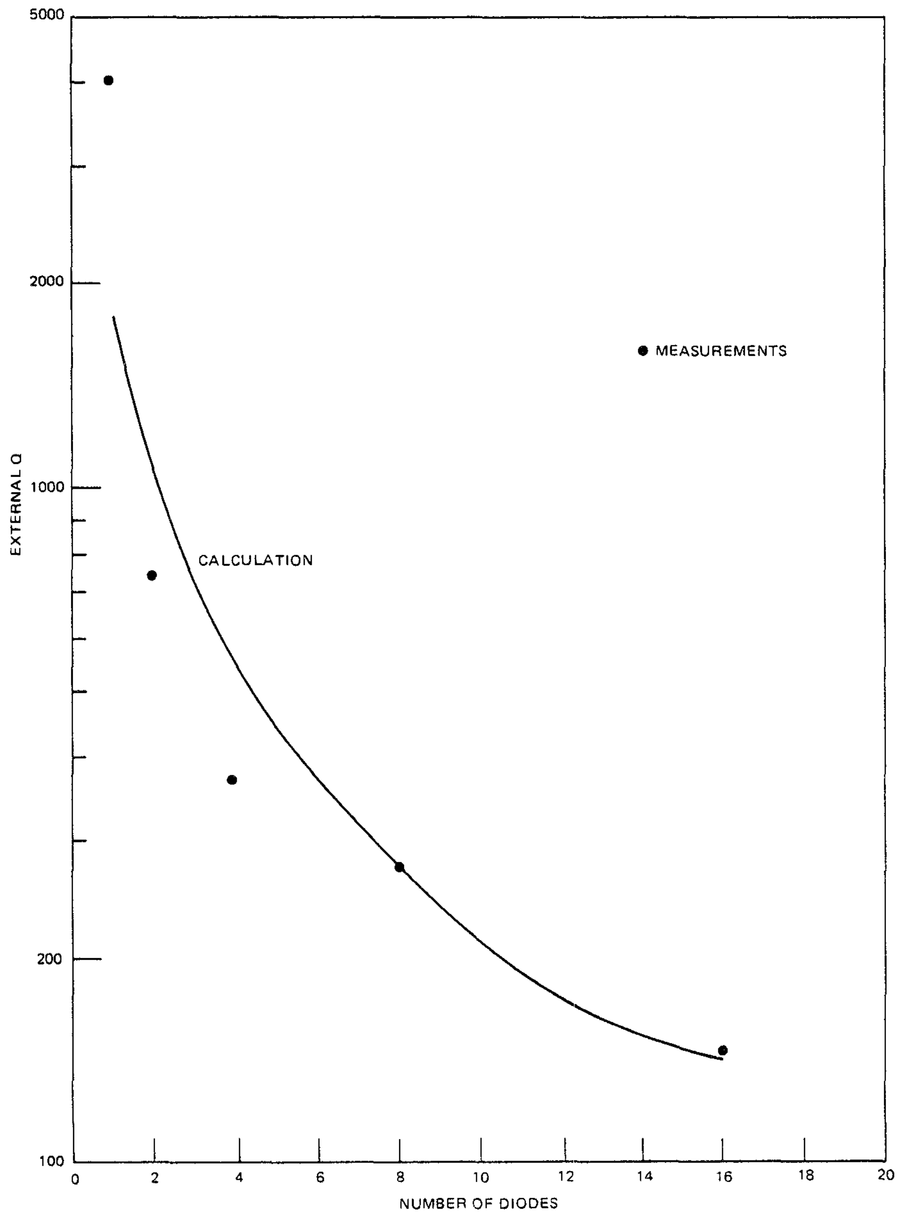

Fig. 4. The effect of the number of diodes upon Q_{ext} in a 16-diode power combiner.

For the case of N diodes

$$Z_n = \frac{1}{G_0} + \frac{N_2^2 N}{\sqrt{C/L}\ \{1/Q_a + 1/Q_{ext} + j(f/f_0 - f_0/f)\}} \tag{7}$$

where G_0 is the bias termination admittance, N_2 is the coaxial module to resonator coupling, C is the cavity equivalent capacity, L is the cavity equivalent inductance, Q_a is the unloaded Q, and f_0 is the resonant frequency of the cavity.

Equations (2)–(7) are sufficient to calculate the power produced by the diode. All parameters are measurable from the defining relationships with the exception of the N_2 coupling which must be inferred by measuring the power from a combiner and searching for an N_2 value that satisfies (2), assuming that the combiner is properly tuned. The oscillator power P_o given by (1) has a combining efficiency given by

$$\eta_c = \left(\frac{1}{1 + Q_{ext}/Q_a}\right)\left(1 - \frac{1}{G_0 \operatorname{Re}[Z_N]}\right). \tag{8}$$

Equations (1)–(8) are the basis of a computer program that aids the design of the power combiner by providing component sensitivity calculations, constant frequency curves, and overall circuit insights difficult to acquire experimentally because of the expense and time involved. The parameters of particular interest, because of their ease of adjustment, shown in Fig. 2, are the external coupling probe l_p, the dimensions of the replaceable coaxial module circuit l_1, l_2, and Z_1 and Z_2 the characteristic impedances.

The tunability of the circuit over more than 1 GHz by adjustment of l_1 and l_2 alone when $f = f_0$ is shown by the

TABLE I
REDUCTIONS IN Q_{ext} DUE TO G_L INCREASE

	ρ	Q_{ext}	Q_{ext_1}/Q_{ext_2}	
Case 1	.186	969	Measured	Calculated
Case 2	.621	308	3.15	3.53

TABLE II
Q_{ext} VERSUS COAXIAL MODULE TO RESONATOR COUPLING

Coupling Diameter (inches)	Q_{ext}
.140	3970
.161	986
.273	283

calculated curves of Fig. 3. Because of the relative flatness of the power curves, it is feasable to use the parameter l_2 to obtain a desired frequency without repeated machining of the matching transformer.

III. INJECTION-LOCK BANDWIDTH

The injection-lock bandwidth can be increased in a given power combiner circuit by increasing the number of combined modules loaded with IMPATT's, provided the coupling to the external circuit N_1 is varied appropriately to match the diodes. The reduction of Q_{ext} and, hence, broader injection-lock bandwidth is shown in Fig. 4 along with corresponding measurements up to the case $N=16$.

A second method for broad-banding the TM_{010}-mode cavity is to raise the characteristic conductance of the output circuit G_L of the power combiner. The Q_{ext} reduces by

$$Q_{ext}=\frac{2\pi f_0 C}{N_1^2 G_L} \qquad (9)$$

when the ratio of the diameter of the inner and outer conductors comprising G_L, ρ, is increased as shown in Table I.

The higher conductance line used for broad-banding the power combiner is matched to the external circuit with a quarter-wave transformer or a multiple-step transformer.

Broad-banding of the power combiner is also achieved by increasing the coaxial coupling between the IMPATT modules and the resonating cavity. For three increasing diameters of the coaxial circuit, having therefore increased coupling, the Q_{ext} for the single-diode case decreases as shown in Table II.

This reduction technique for Q_{ext} is similar to the previously reported method of moving the coaxial modules closer to the center of the cavity in order to achieve increased coupling to the combiner magnetic field [6].

IV. CONCLUSION

In the TM_{010}-mode power combiner, the Q_{ext} is decreased, and, therefore, the injection-lock bandwidth is increased by: 1) increasing the coupling between the external circuit and the resonator, 2) increasing the coupling between the IMPATT module and the resonator, 3) increasing the number of diodes combined, and 4) increasing the characteristic conductance of the external circuit.

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