EFFICIENT POWER COMBINING

Michael Dydyk
Motorola Government Electronics Division
Scottsdale, Arizona 85252

ABSTRACT

The objective of this paper is to establish understanding of the single/multi-mode oscillator circuits used in combiners

A model is developed with emphasis on the selection and realization of the input/output coefficients, optimum stabilizing and output loads, equalizing network synthesis and other cogent features.

The application of this theory to the highly successful and efficient design of J-band pulsed oscillators is discussed.

SUMMARY

The need for higher and higher power pulsed, solid-state microwave oscillators is steadily expanding due to increased complexity of radar, communication, countermeasures and fuzing systems. As we all know, there is an aversion to using tubes/magnetrons for these applications because of excessive size, weight, prime power and most of all poor reliability One way to meet this demand is to continuously work the problem of increasing the output power and efficiency of the semiconductors and circuits used to generate the microwave energy.

Great progress has been made, in the past several years, in the output power of microwave solid state devices such as IMPATT and Gunn diodes However, there is at this time still a wide gap between the solid-state device and magnetron capability, on a one-to-one basis. To reduce or eliminate this gap it is beneficial to explore the full potentials and establish limitations of a complementary method for higher power, namely, the combination of output power from several devices, the subject of this paper

The concept of summing the output power from several oscillators, by combining their outputs to a single resonator, is not new As far back as 1939, Zotu patented such a scheme, where he summed a number of triode oscillators. The utilization of IMPATTs and Gunns in this concept, as the active devices, presents unique problems

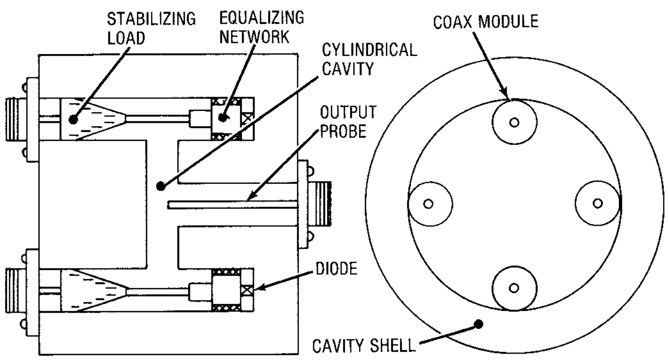

Figure 1. Cylindrical Cavity Power Combiner Realization

Solutions to some of these problems have been established by such investigators as Harkless[1], Kurokawa[2], and Harp and Stover[3]. The approach undertaken by Harp and Stover is by far superior and is used in this paper as the basic building block.

Figure 1 shows the schematic diagram realization of this approach when a plurality of individual coaxial oscillator circuits are spaced around a cylindrical cavity operating in the TM010 mode. The combining cavity presents each diode with the proper impedance for oscillation only in a narrow frequency band centered at the resonant frequency of the cavity. To obtain an insight into the full potential and limitation of this approach, it is necessary to look at the equivalent circuit of the individual module making up the power combiner as shown in Figure 2.

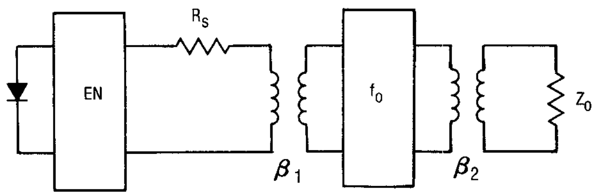

Figure 2. Equivalent Circuit of Power Combiner Module

By replacing the diode and its equalizing network with a voltage generator and its associated generator impedance, it is shown that the insertion loss of this circuit is given by

$$(1) \quad IL = 10 \log_{10} \left(1 + \frac{R_S}{R_C}\right)\left(1 + \frac{1}{\beta_2}\right)$$

where R_C is the impedance seen looking into the cavity and given by

$$(2) \quad R_C = \frac{2Z_0\beta_1}{1+\beta_2}$$

It becomes immediately obvious that the efficiency of this oscillator depends highly on the ratio of the stabilizing load impedance (R_S) to the real part of the input impedance looking into the cavity (R_C). This efficiency improves with a decreasing ratio, becoming optimum as this ratio decreases to zero. The maximum real input impedance of the resonant cavity occurs at the resonant frequency and decreases rapidly, with a change in frequency. This means that, in order to obtain maximum efficiency, the diode has to be made resonant by the equalizing network which is extenal to the resonant cavity.

In theory this can be done, but in practice becomes very difficult and tedious without a complete characterization of the circuit and the diodes. Only the circuit characterization is discussed in this paper, while the diode characterization can be performed with a modification of the technique described in reference (4).

Since the input/output coupling coefficients of the cavity play such an important part in the design of oscillators under consideration, it is important to have an analytical appreciation for their realization. A literature search revealed that no such analysis was available.

With the help of the electromagnetic theory and Figure 3 the input coupling coefficient is shown to be

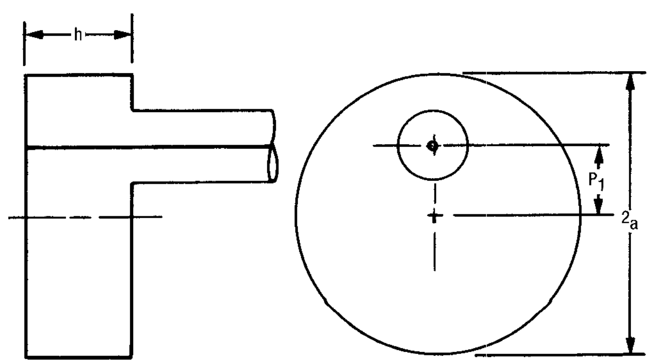

Figure 3. Top and Side View of a Cylindrical Cavity Resonator

$$(3) \qquad \beta_{10} = \frac{hQ_o}{\pi \epsilon_o a^2 \omega_o} \times \left[\frac{J_o(X_{01}P_1/a)}{J_1(X_{01})} \right]^2$$

The self-inductance as given by

$$(4) \qquad L_e = \frac{60h \cosh^{-1}}{\sqrt{\epsilon_R}C} \left[\frac{1}{2} \left(\frac{4a^2 + d^2 - 4P_1^2}{2ad} \right) \right]$$

is developed by considering the cavity as the output conductor of an eccentric transmission line.

The self-inductance modifies the input coupling coefficient to that of

$$(5) \qquad \beta_1 = \frac{\beta_{10}}{1 + \left(\frac{\omega L_e}{2Z_o} \right)^2}$$

which would be the actual measured coupling coefficient.

The output coupling coefficient, which is realized via a probe and modeled as shown in Figure 4, is dependent on

$$(6) \qquad \beta_{20} = \frac{Q_o \lambda_o^3 \eta}{Z_o a^2 (2\pi)^3 \pi h} \times \left[\frac{\tan kg}{2} \times \frac{J_o(X_{01}P_1/a)}{J_1(X_{01})} \right]^2$$

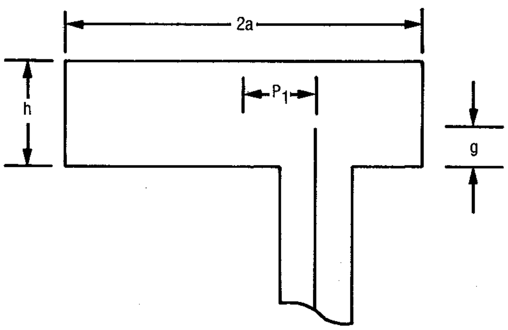

Figure 4. Side View of the Output Probe

The self capacitance (C_p) is obtained with the aid of the fringing capacitance extracted from the work reported by Whinnery[5]. This self-capacitance modifies the output coupling coefficient to

$$(7) \qquad \beta_2 = \frac{\beta_{20}}{1 + \left(\frac{1}{\omega C_p Z_o} \right)^2}$$

Both results for β_1 and β_2 have been verified experimentally with measured results in close agreement to theory.

The choice of R_s is not arbitrary and has to be selected with great care. To maximize efficiency and to add an additional degree of freedom for purposes of tuning the diode, other investigators have incorporated flat profile stabilizing loads. However, such loads cause arbitrary impedances to occur outside of operating range, which is precisely the reason why these loads have been incorporated. To prevent out-of-band oscillation it is necessary to have a controlled impedance, which can best be accomplished with a matched stabilizing load.

The theory developed was applied to the design of a pulsed oscillator operating at J-band using Si double-drift IMPATT diodes. Reasonable care was exercised to obtain the kind of efficiency expected as dictated by Eq.(1). However, without excessive "diddling" it was not possible to do so. Therefore, it became obvious that in order to extract maximum power from the diode the stabilizing load has to be removed somehow at the operating frequency but be available everywhere else.

The ultimate solution is shown in Figure 5 where another cavity is added to the circuit. This second cavity is tuned to the same frequency as the main cavity and, in conjunction with the $\lambda o/4$ transmission line, effectively short-circuits the stabilizing load only at the operating frequency. This combination makes the oscillator highly efficient, permits a degree of mechanical tunability while maintaining efficiency and, most important, both features are easily achievable.

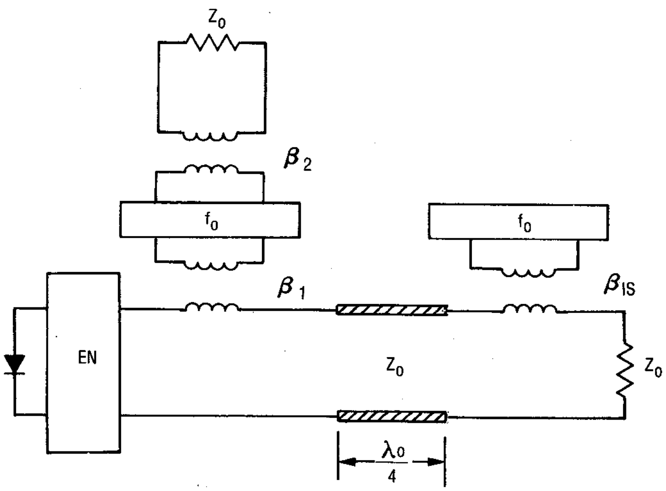

Figure 5. Equivalent Circuit of a Two Cavity Oscillator

This paper develops equations showing the effect of this second cavity on efficiency, optimum output coupling coefficient and Q_{ext} for both the simple as well as N diode oscillators.

Finally, experimental results are discussed on single-, three- and six-diode oscillator designs. The power outputs of each oscillator were: 21, 60 and 105 watts peak, respectively, operating at J-band with 11 percent duty cycle. A photograph of a complete J-band transmitter is shown in Figure 6.

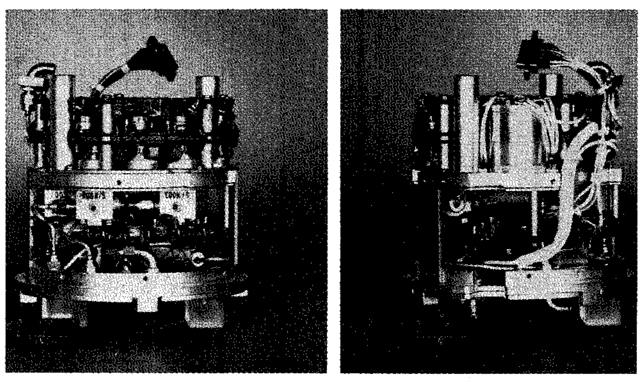

Figure 6. Complete J-Band Transmitter

[1]E. T. Harkless, U.S. Pat. No. 3,534,293, granted Oct. 13, 1970.

[2]K. Kurokawa, U.S. Pat. No. 3,628,171, granted Dec. 14, 1971.

[3]R. S. Harp and H. L. Stover, "Power Combining of X-band IMPATT Circuit Modules", ISSCC Digest of Technical Papers, pp. 118-119; Feb 1973.

[4]Michael Dydyk, "A Step by Step Approach to High Power VCO Design", to be published in Microwaves February, 1979.

[5]J. R. Whinnery, H. W. Jamieson, and Theo Eloise Robbins, "Coaxial-Line Discontinuities" Proc. of IRE (November, 1944), pp. 695-709.