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A Multiple-Device Cavity Oscillator Using Both Magnetic and Electric Coupling Mechanisms

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***Abstract*—This paper presents a novel concept to increase the number of active devices combined in a cavity oscillator by coupling them to both electric and magnetic fields inside the cavity. The structure employs probes and coaxial lines for electric and magnetic coupling, respectively. The sum of the output powers from individual devices combined can be obtained by properly adjusting the coupling factors of the circuit. Operation principles of the circuit are analyzed for probe coupling, and results are applied to explain the operation of the circuit when both probe and coaxial coupling are used. The circuits described here are free from moding instabilities. Prototype circuits have been constructed at *X*-band, using Gunn diodes, for experimental confirmation of the theory developed.**

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I. Introduction

THE SINGLE-TUNED oscillators invented by Kurokawa *et al.* [1] and Harp *et al.* [2] have received considerable development and application as the most successful power combining techniques at microwave and millimeter-wave frequencies [3]–[7]. Nevertheless, the increasing need for higher and higher output power may

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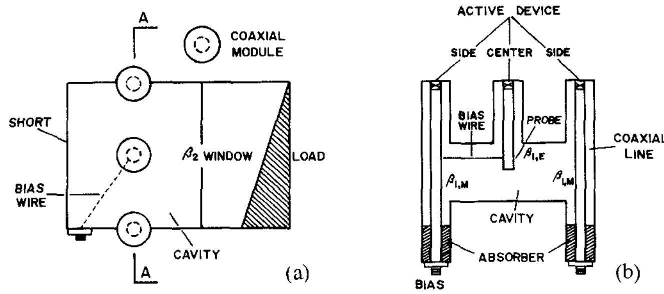

Fig. 1. Circuit diagram of the 3-device oscillator. (a) Top view. (b) Cross-sectional view at AA.

tempt one to develop new methods to increase the number of devices in a certain size of cavity. In the oscillator structures reported so far, the outputs of active devices are coupled mainly to either the magnetic field [1], [2], or the electric field [8] inside a cavity, but not both. Therefore, an approach which could otherwise increase the total number of devices (hence, output power) is overlooked. Perhaps the reason for the void of any reported work on incorporating both approaches has been the lack of an appropriate structure which can satisfy the oscillation condition for both and can ensure a mode-free operation at the same time. For this purpose, the probe-coupling oscillator reported recently [8] by two of the authors is useful. Due to simple adjustability of the circuit parameters in this oscillator, it can be added to the Kurokawa oscillator to increase the total number of devices per half-guide wavelength in a cavity. Using this circuit, we have built a new oscillator structure which is shown in Fig. 1. In this new structure, use is made of a probe to excite mainly the electric field and coaxial lines, to excite mainly the magnetic field inside the cavity. This paper describes the design procedure and operation principles of the proposed structure. Emphasis is placed on the analysis of the probe-coupling oscillator and its mode-free operation. X-band prototype circuits have been built to confirm the theory.

II. Circuit Description

Fig. 1 shows a 3-device oscillator structure schematically. Active devices on the sides are coupled to the magnetic field, and the device at the center is coupled to the electric field inside a rectangular waveguide cavity where the fields are maximum for the dominant TE_{101} mode. Coupling is by means of the coaxial lines and probe, respectively. The cavity is short circuited at one end, and coupled to a match load through an inductive window at the other end. DC bias is applied to the center device using a thin wire connected to the probe inside the cavity, and to each side device through the inner conductor of the respective coaxial line. The combined output power from all the devices can be obtained by proper adjustment of the input coupling factor $\beta_{1,E}$ of the center device, the input coupling factor $\beta_{1,M}$ of the side devices, and the output coupling factor β_2.

The structure can essentially be considered as a combination of the Kurokawa oscillator and probe-coupling oscillator. Therefore, to explain the operation, one may first treat the two circuits separately and then apply the results to the new circuit. The behavior of the Kurokawa oscillator is, however, well known and described in the literature extensively. In the following section, prior to analyzing the 3-device oscillator, we treat the principles of operation, moding stability, and features of the probe-coupling oscillator due to which it can be combined with the Kurokawa oscillator.

III. Analyses

A. Probe-Coupling Oscillator

A probe-coupling oscillator is shown schematically in Fig. 2. An active device, represented by the impedance $-Z_d(A)$, where A is an amplitude of the device current, is mounted at one end of a coaxial transformer with a characteristic impedance Z_c and a length l_c. The other end of the transformer is coupled to the cavity, where the electric field is maximum for the dominant TE_{101} mode, by means of a probe which is an extension of the center conductor of the transformer. DC bias can be applied to the device using a thin wire, brought in through a side wall of the cavity, and connected to the probe. An equivalent circuit of the oscillator is shown in Fig. 3, where the resonant cavity is represented by a parallel $R_0L_0C_0$ circuit with R_0 as cavity internal losses and $\omega_0 = 1/\sqrt{L_0C_0}$ as the resonant frequency of the dominant mode. X_p is the probe series reactance and the ideal input transformer $(n_1\colon 1)$ represents the probe coupling [9]. The inductive window is represented by the ideal output transformer $(n_2\colon 1)$.

To satisfy the oscillation condition at resonance, the sum of the device impedance $-Z'_d(A)$ and circuit impedance $Z_E(\omega)$ for the TE_{101} mode at the reference plane BB should be equal to zero. The locus of $Z_E(\omega)$ varies on the Smith chart as shown by the circle in Fig. 4. The device line $Z_d(A)$, on the other hand, may appear as illustrated in the same figure. (This is actually the measured device line of the Gunn diodes used in the experiments at 9.7 GHz.) Therefore, a certain length of the coaxial transformer is necessary to transform $Z_d(A)$ to $Z'_d(A)$ to fulfill the oscillation condition, i.e.,

$$R'_d = R_E = \frac{Z_c\beta_{1,E}}{1+\beta_2} \tag{1}$$

where $-R'_d = \mathrm{Re}\{-Z'_d(A)\}$, $R_E = \mathrm{Re}\{Z_E(\omega)\}_{\omega=\omega_0}$, and $\beta_{1,E}$ and β_2 are the input and output coupling factors, respectively. For a given frequency, $\beta_{1,E}$ and β_2 can be adjusted simply by changing only the probe length d_p and window width d_w, respectively (Appendix I). Once condition (1) is satisfied, the device can be operated at optimum A to generate maximum available power P_{av}, by properly adjusting $\beta_{1,E}$ and β_2. The output power, then, is equal to ηP_{av} where η, the circuit efficiency, is given by

$$\eta = \frac{\beta_2}{1+\beta_2}. \tag{2}$$

With respect to (1) and (2), by selecting both $\beta_{1,E}$ and β_2 large, the output power approaches P_{av}.

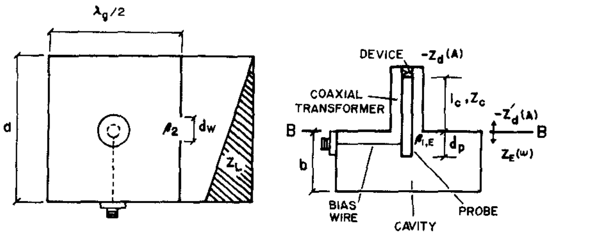

Fig. 2. A single-device probe-coupling oscillator. (a) Top view. (b) Cross-sectional view at AA.

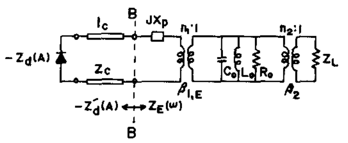

Fig. 3. Equivalent circuit of the oscillator shown in Fig. 2.

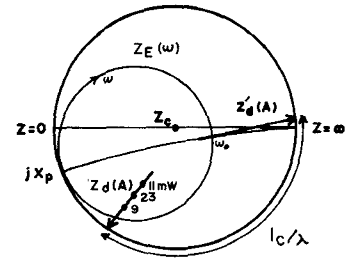

Fig. 4. Graphic realization of oscillation condition at cavity resonant frequency for probe-coupling oscillator.

A multiple-device structure using the probe-coupled oscillator employs N active devices coupled to a common cavity and spaced half a guide wavelength apart. This structure and its equivalent circuit are shown, respectively, in Figs. 5 and 6. The oscillation condition can be satisfied, at resonance, if

$$R'_d = \frac{NZ_c\beta_{1N}}{1+\beta_{2N}} = \frac{Z_c\beta_{1,E}}{1+\beta_2} \tag{3}$$

where β_{1N} and β_{2N} are the input and output coupling factors of the N-device structure, respectively.

The probe-coupling oscillator is free from moding instabilities. For the resonant modes of the cavity other than the dominant one, the coupling between the probe and the cavity is weak. Thus, no intersection between the impedance locus and device line can be realized. Experimentally, no oscillations at other resonant frequencies were observed during the circuit adjustments using Gunn diodes which generally exhibit negative resistance over, say, a frequency range 7–15 GHz.

On the other hand, for an N-device structure, there are as many as N solutions to the voltage developed across the parallel circuit of Fig. 6., for the dominant mode [1], [10]. However, except for one solution, the contributions of devices currents to this voltage sum to zero. Hence, the parallel circuit will be represented by a short circuit, and each device will observe the reactance X_p of its respective probe transformed by the coaxial transformer. Under this circumstance, no oscillation condition can be satisfied as

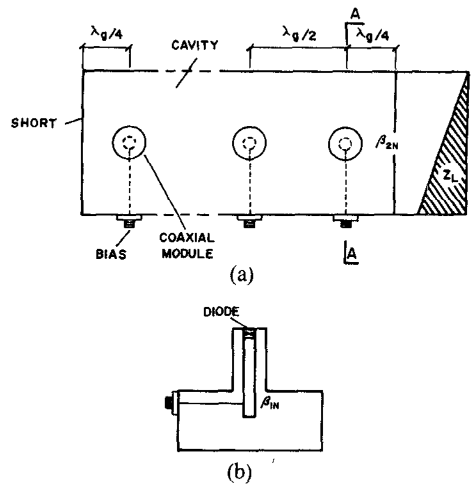

Fig. 5. An N-device probe-coupling oscillator. (a) Top view. (b) Cross-sectional view at AA.

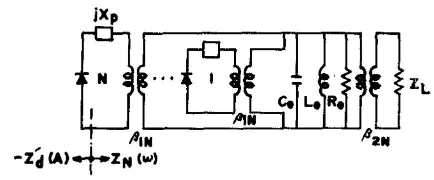

Fig. 6. A symmetric equivalent circuit of the N-device probe-coupling oscillator.

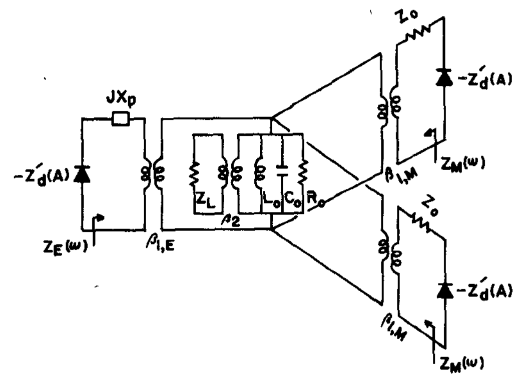

Fig. 7. Equivalent circuit of the 3-device oscillator shown in Fig. 1.

long as $Z'_d(A) \neq jX_p$, a condition which can be achieved by proper transformation of the device line.

Prototype circuits built support the theory described and promise a mode-free operation for the single-device as well as multiple-device probe-coupling oscillators.

B. 3-Device Oscillator

Owing to simple adjustability of the input coupling factor $\beta_{1,E}$ in the probe-coupling oscillator, it can be combined with the Kurokawa circuit to construct the 3-device oscillator of Fig. 1. An equivalent circuit of this configuration is shown in Fig. 7 where three identical devices are coupled to a common cavity. Z_0 represents the flat type absorber used in each side coaxial line, $-Z'_d(A)$ the transformed impedance of the devices, and $Z_M(\omega)$ and $Z_E(\omega)$ the respective circuit impedances for the TE_{101}

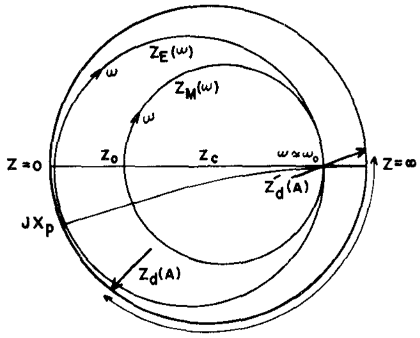

Fig. 8. Graphic realization of oscillation condition at a frequency in the vicinity of cavity resonant frequency for the 3-device oscillator.

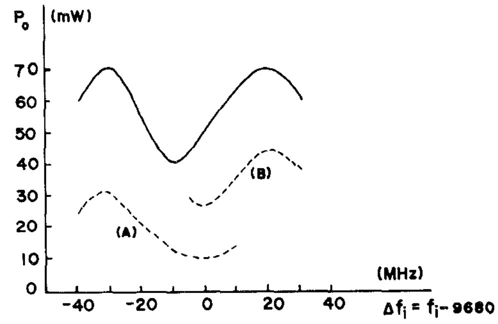

Fig. 9. Injection-locking behavior of the 3-device oscillator.

mode. The effects of the discontinuities introduced in the coaxial lines and the waveguide cavity are incorporated into the parallel circuit representing the cavity. Neglecting the frequency dependences of Z_0 and jX_p, one can write

$$Z_M(\omega) = Z_0 + \frac{Z_c\beta_{1,M}}{jQ_0(\omega/\omega_0 - \omega_0/\omega)+1+\beta_2} \tag{4}$$

$$Z_E(\omega) = jX_p + \frac{Z_c\beta_{1,E}}{jQ_0(\omega/\omega_0 - \omega_0/\omega)+1+\beta_2} \tag{5}$$

where $Q_0 = R_0/\omega_0 L_0$ is the internal Q of the cavity, β_2 the output coupling factor, and $\beta_{1,E}$ and $\beta_{1,M}$ are the input coupling factor for the center device and the side devices, respectively. $\beta_{1,M}$ is practically fixed, but $\beta_{1,E}$ can be simply changed with the probe length.

To satisfy the oscillation condition at a frequency in the vicinity of the cavity resonant frequency ω_0, all the devices should see identical impedances, i.e., $Z'_d(A) = Z_M(\omega) = Z_E(\omega)$. The loci of $Z_M(\omega)$ and $Z_E(\omega)$ vary on the Smith chart as shown by the circles in Fig. 8. Therefore, once the device line is transformed properly, the two loci can coincide with each other in the vicinity of ω_0 by adjusting $\beta_{1,E}$. Then by proper selection of window width, effectively β_2, all the devices can be operated near the maximum available power point, and the output power can be as high as the sum of the powers from individual devices.

The 3-device oscillator is free from moding problems. For proof, one may apply the discussion given in this section earlier. Moreover, since, from Fig. 8, $|Z'_d(A)| \neq Z_0$ and $|Z'_d(A)| \neq |jX_p|$, the circuit is prevented from oscillating in antiphase modes of no RF output [1], [10].

IV. Experiments

The validity of the descriptions given for the circuits analyzed was verified at X-band using standard rectangular waveguide (22.9 mm × 10.2 mm) and Gunn diodes (NEC GD 511AA, 15–30 mW).

A. Probe-Coupling Oscillator

Using the configuration of Fig. 2, four single-device oscillators were built, and later stacked together to construct a multiple-device oscillator. To prevent any disturbance of the fields inside the cavity by the bias wires, they were placed perpendicular to the electric field and connected to the mid-length of the probes. Actually, different points over the probes' length were tried; the mid-length point was found to be a proper position. In addition, chip capacitors were used outside the cavities to minimize the effect of the biasing circuit on the RF circuit. The physical specifications and performance data of the single-device oscillators are summarized in Table I. By cascading these oscillators and using an optimum window measuring 12 mm in width, output power of 98 mW was obtained from a 4-device oscillator at 9618 MHz. The operation of the single-device as well as multiple-device oscillators was stable and neither spurious oscillations nor jump phenomena were observed during the circuit adjustment, confirming the single-tuned behavior of the probe-coupling oscillator.

TABLE I
Physical Specifications and Performance Data of Single-Device Probe-Coupling Oscillators

OSCILLATOR NO.	COAXIAL TRANSFORMER Z_c (OHM)	COAXIAL TRANSFORMER l_c (mm)	PROBE LENGTH d_p (mm)	WINDOW WIDTH d_w (mm)	OUTPUT POWER (mW)	OSCILLATION FREQUENCY (MHz)
1	50	5.5	3.5	8.5	24.5	9630
2	50	5.5	3.5	8.5	25	9600
3	50	5.5	3.5	8.5	23.5	9610
4	50	5.5	3.5	8.5	21	9620

B. 3-Device Oscillator

A 3-device oscillator was built using the circuit of Fig. 1. First, the side devices were mounted at one end of 50-Ω coaxial lines, and circuit adjustment was made to find the proper position of the devices, as well as the absorbers (ECCOSORB), using a 6.5-mm window. This provided a CW-output power of 40 mW. Then, the center device was mounted at one end of a 50-Ω coaxial transformer measuring 8 mm in length, of which 2.5 mm was extended into the cavity as a probe. By doing so and readjusting the window width to 7.8 mm, the output power increased to 65 mW at a frequency of 9680 MHz. The operation was stable and no spurious oscillation was noted. The spectrum was clean, and the oscillation frequency as well as the output power could be changed with no jump, as the bias voltage was varied from 5 to 11 V.

The injection-locking behavior of the 3-device oscillator was examined on several devices and circuits. After optimizing the loading condition, an injection signal providing a gain of 10 dB was applied to the oscillator and the output power P_o and the output frequency were monitored while sweeping the injection frequency f_i. The results are shown in Fig. 9. The double-peak characteristic of the curve may promise the applicability of the 3-device oscillator to both power-combiner and amplitude-limiter circuits which utilize the peak and the valley of the injection-locking curve of injection-locked oscillators [12], [13], respectively.

From the injection-locking experiments it was also found that by adding the center device to the Kurokawa oscillator, the external Q of the circuit is lowered by a factor of 2. The measured external Q's for the Kurokawa, probe-coupling, and 3-device oscillators were 370, 250, and 185, respectively.

V. Conclusions

A new concept was introduced to increase the number of active devices per half-guide wavelength from 2 to 3 in a cavity. The approach employed couples the outputs of active devices to both electric and magnetic fields inside the cavity. By proper adjustment of circuit parameters, the sum of the output powers from individual devices can be obtained. The new circuit is free from moding problems. Prototype circuits were constructed and tested to confirm the principles described. The experiments have been conducted at X-band using low power Gunn diodes. In the future, we apply the approach to higher frequency bands and other high-power devices such as IMPATT's. Although the examples given in this paper deal with rectangular waveguides, the description is also applicable to other structures such as cylindrical waveguides. Experimental works are currently under way to develop the combiners containing 3-N active devices in a cavity by employing the 3-device building-block structure described. Preliminary results obtained are quite promising.

Appendix I
The Input and Output Coupling Factors of the Probe-Coupling Oscillator

A. Input Coupling Factor

The input coupling factor $\beta_{1,E}$ is defined as the ratio of the cavity losses seen by the probe at the reference plane BB to the losses in the input circuit with the device replaced with a match termination Z_c. In accordance with [9] and some manipulations, one can write

$$\beta_{1,E} = \frac{n_1^2 R_0}{Z_c} = \left(\frac{Q_0\sqrt{\mu/\epsilon}\,\lambda^3}{ab\pi^3 Z_c \lambda_g} \right) \tan^2(\pi d_p/\lambda)$$

where d_p is the physical length of the probe, a and b are waveguide dimensions, and other symbols represent their customary meaning.

B. Output Coupling Factor

The output coupling factor β_2 is defined as the ratio of the cavity losses to the output load resistance transformed by the window. With respect to [11]

$$\beta_2 = \frac{R_0}{n_2^2 Z_L} = \left(\frac{2Q_0\lambda^2 a^2}{\pi\lambda_g^4} \right) \tan^4(\pi d_w/2a)$$

where d_w is the window width.

For a given frequency, $\beta_{1,E}$ and β_2 can be simply adjusted by changing only the probe length and window width, respectively.

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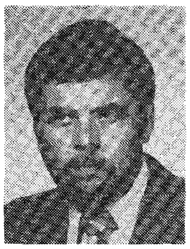

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Thermally Induced Switching and Failure in p-i-n RF Control Diodes

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Abstract —**This paper measures and analyzes a thermally induced, breakdown-like effect in p-i-n RF switching diodes. The effect is found to be due to thermally generated carriers increasing the *I*-region conductivity and loss. This is a positive feedback situation which, with increasing power levels, eventually causes the diode to switch to a low-impedance state. In the low-impedance state, further increases in temperature have a negative feedback effect on the absorbed power and hence this mode is stable with a very large hysteresis effect. Unfortunately, the high temperatures encountered in the low-impedance mode (~ 400°C) have a detrimental effect on diode reliability. The threshold power at which switching to this mode occurs can be increased somewhat by reverse biasing the diode or improving its heat sink.**

I. INTRODUCTION

RECENT, APPARENTLY unexplained, failures in a 500-MHz p-i-n switching diode (HP 5082-3081) in a receiver front-end caused us to investigate this problem. It was found that even when the diode was reverse biased, coupling of a few watts of power from a nearby CW transmitter would cause the diode to switch to a stable, high temperature, low-impedance state. The temperatures in this state (~ 400°C) caused diode failure due to melting of the chip bond solder joint. Experimental and theoretical investigations of this effect are described in this paper.

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II. EXPERIMENT

The diode, an axial lead, glass packaged device, has an I-region width of $\sim 175\ \mu$ and a cross-sectional area of $\sim 4.9 \times 10^4\ \mu^2$. The breakdown voltage is > 100 V with an allowable dissipation of 250 mW at 25°C. The diode was placed at the end of a 50-Ω transmission line and connected through a network analyzer to a variable power 50-Ω generator at 500 MHz. In the first test the diode was held at zero bias by a dc-return choke. Fig. 1 shows the measured results versus applied RF power. Fig. 1(a) and (b) show that as the power is initially increased from zero, the diode impedance is $\gg 50\ \Omega$ ($|S_{11}| \sim 0$ dB, $< S_{11} \sim 0°$).

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