Efficient Power-Combining of Nonidentical Double-Diode Waveguide Oscillator-Modules

S. Sarkar and B. V. Ramana Reddy

***Abstract*—Power-combiner formed by cascading nonidentical double-diode waveguide oscillator modules is studied. Theoretical analysis shows that power reflection between the diode mounting planes of two immediately neighboring modules is reduced if the output side module of the two is of lower power output. Decrease in reflection increases power-combining efficiency. The relative positions of two neighboring nonidentical modules is therefore important for the combiner design. Results obtained from experimental studies confirm this.**

I. Introduction

SOLID-STATE devices, such as Gunn's Impatt's, etc., are widely used for millimeter and microwave power generation. The limited power outputs of these devices, however, fail to meet the power requirements of many potential applications. To overcome this limitation, following the pioneering work of Kurokawa [1], several techniques to power combine a number of such active devices have been evolved over the years [2], [3].

The simplest form of power combiner is a double-diode oscillator. Some of the power combiners are constituted by a cascade of a number of double-diode oscillator modules. Waveguide power combiners of this type have yielded very high power-combining efficiencies [4], [5]. All theoretical and experimental works reported in literature, however, are concerned with combination of identical oscillator modules. The advantage of using identical modules is lower power reflection within the composite waveguide structure. This helps in achieving high power combining efficiency. For identical modules, identical active devices are required. Procurement of identical active devices generally prove to be expensive. Furthermore, active devices like Gunn, Impatt etc., are not manufactured by the native industries of most of the third world countries. Thus, the cost of identical module fabrication is a greater burden on the exchequer of a third world country. In view of this it is of interest to explore the possibility of power combining nonidentical modules. This letter deals with waveguide power combiner formed by nonidentical double-diode oscillator modules. Reflection in such a system is theoretically analyzed and a method of reducing reflection for higher power-combining efficiency is proposed along with supporting experimental results.

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II. Theory

Commonly, a double-diode waveguide oscillator consists of a mount-pair housed inside a rectangular waveguide section. The mount-pair is formed by two identical cylindrical diode mounting posts, where each post mounts one diode. The two diodes thus mounted are also identical. The axes of the posts lie in the same transverse plane of the waveguide. An adjustable short at one end of the waveguide section provides tuning facility. In this and subsequent sections, by an oscillator module we mean a double-diode oscillator structure with its tuning short removed. When a power combiner is formed by a cascade of such modules, one of the end modules retains the adjustable short. Power is extracted from the module at the other end.

When two or more modules are cascaded, the composite structure has an array of mount-pairs as shown in Fig. 1. Two mount-pairs are considered identical when the diode mounting structures have same physical dimensions and all diodes yield the same power output at the operating frequency of the combiner. If any of these requirements are not satisfied, the mount-pairs are nonidentical. For identical mount-pairs, Nogi and Fukui [5] obtained an analytical expression for reflection coefficient at a plane halfway between two adjacent mount-pairs. Assuming all mount-pairs to be nonidentical we generalized the approach of Nogi and Fukui. The reflection coefficient between $(k-1)$th and kth mount-pair thus obtained is

$$\Gamma_k = \frac{1 + \dfrac{V_{k+1}}{V_k}\mathrm{Sin}\left(\psi_{k,k-1} + \dfrac{\phi_k}{2}\right)\Big/\mathrm{Sin}\dfrac{\phi_k}{2}}{1 - \dfrac{V_{k-1}}{V_k}\mathrm{Sin}\left(\psi_{k,k-1} - \dfrac{\phi_k}{2}\right)\Big/\mathrm{Sin}\dfrac{\phi_k}{2}}; \quad k = 2, 3 \cdots N \tag{1}$$

where V_{k-1} and V_k are the rf voltage amplitudes at the $(k-1)$th and kth nodes (Fig. 1) respectively, ϕ_k is the electrical length between the two mount-pairs, and $\psi_{k,k-1}$ is the phase difference between the two node voltages.

If a power combiner circuit is optimized for maximum power output then at the kth node power generated is

$$P_k = \tfrac{1}{2} r_k^2 g_{ok} V_k^2 \tag{2}$$

where

- r_k coefficient of mount coupling reduction,
- g_{ok} magnitude of a normalized negative conductance which arises because of the two diodes of the mount-pair, and
- V_k dependent on r_k, g_{ok} and a parameter that determines the rate of change of individual diode negative conductance with rf voltage at the diode terminals.

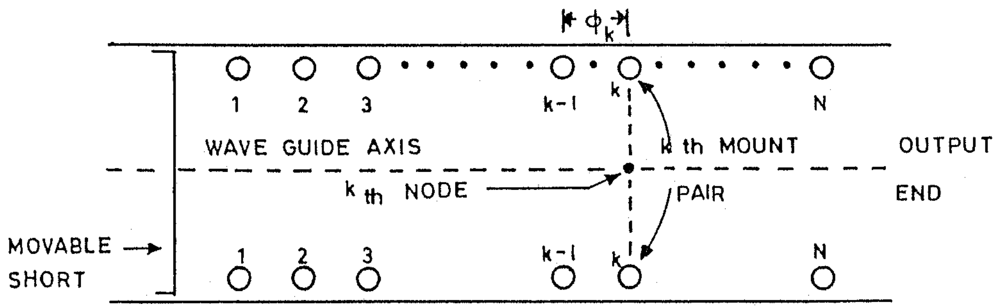

Fig. 1. Mount-pair array. Circles indicate diode mounts.

Assuming equal r_ks $(=r)$ and θ_ks for all mount-pairs and diodes respectively, and substituting (2) in (1) along with the expression for V_k as used by Nogi and Fukui [5], it can be shown that

$$\Gamma_k = \frac{1+\left(\frac{P_{k-1}}{P_k}\right)^{1/4} \mathrm{Sin}\left(\psi_{k,k-1}+\frac{\phi_k}{2}\right) \Big/ \mathrm{Sin}\frac{\phi_k}{2}}{1-\left(\frac{P_{k-1}}{P_k}\right)^{1/4} \mathrm{Sin}\left(\psi_{k,k-1}-\frac{\phi_k}{2}\right) \Big/ \mathrm{Sin}\frac{\phi_k}{2}} \quad (3)$$

where

$$\psi_{k,k-1} = -\,\mathrm{Sin}^{-1}\left[\left(\frac{P_{k-1}}{P_k}\right)^{1/4} \beta_k \mathrm{Sin}\phi_k\right] \quad (4)$$

and

$$\beta_k = \frac{r^2}{2g_{o_{k-1}}} \sum_{l=1}^{k-1} g_{ol}^2; \qquad k = 2, 3, \cdots, N. \quad (5)$$

For identical mount-pairs, (3) and (4) reduce to (38) and (17) of [5].

Fig. 2 illustrates the variation of reflection coefficient with the ratio of power generated at the $(k-1)$th node to that at the kth node. It shows that reflection coefficient can be appreciably large if the power-ratio is low. A large reflection coefficient gives rise to a large amplitude of standing wave. This is not desirable for an actual waveguide power-combiner, as large amplitude of standing wave results in considerable loss of power in the form of waveguide–ohmic loss. Thus, the fall in reflection coefficient with increase in the power ratio implies that the relative position of two immediately neighboring modules should be such that the lower power one is on the output side. This requirement is more important at higher frequencies, where the waveguide losses are higher and combining efficiency is lower as a consequence. Fig. 2 also shows that reflection coefficient depends on parameter β_k. This parameter is a measure of the total negative conductance, which is coupled to the circuit by mount-pairs 1 through $k-1$. The fall in reflection coefficient with increase in β_k indicate that diodes of higher negative conductance are preferable.

It may be noted that ϕ_k is a function of β_k [4]. However, for small values of β_k, ϕ_k mainly depends on the susceptances presented at the mount-pair planes. Our assumption that $\phi_k\,(=0.41\pi)$ is independent of β_k is, therefore, applicable to smaller values of k.

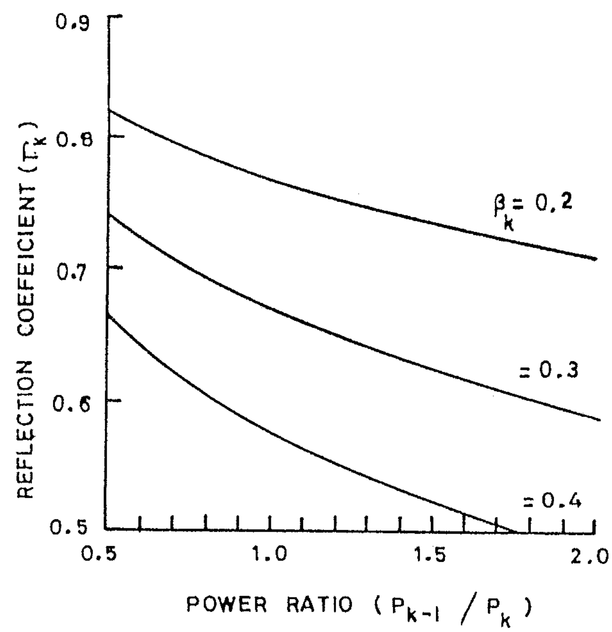

Fig. 2. Reflection coefficient between adjacent mount-pairs as function of the ratio of power generated at the mount-pair nodes with β_k as the parameter and $\phi_k = 0.41\,\pi$.

III. Experiment

The theoretical analysis presented shows that in a cascade of nonidentical double-diode oscillator modules, power-loss due to reflection can be reduced by placing the modules in the descending order of their individual power outputs in the direction of the output end. That is, with such a placement of modules a higher power-combining efficiency can be achieved. To verify this, experiments are carried out with two typical double-diode waveguide Gunn oscillator modules of the type described in Section II. For this purpose VR90 waveguide and mounting posts of 3 mm diameter are used. The separation between each post and its nearest side wall is 1 mm. The diodes are located halfway between the broad walls of the waveguide. By providing a sliding short at one end, the power output and oscillation frequencies of each module is measured. In the measurement setup, the oscillator circuit is optimized, by a slide-screw tuner. The power flowing out of the optimized circuit successively passes through an isolator and a variable attenuator before it is measured by a power meter. A frequency meter placed between the attenuator and power meter measures the frequency. In either case, power output is maximized by applying optimum

TABLE I
POWER-COMBINING EFFICIENCIES AND POWER OUTPUTS OF C1 AND C2 (POWER OUTPUTS OF M1 AND M2: 162 mw AND 138 mw)

Combiner	Maximum power output (mw)	Frequency (Ghz)	Power-combining efficiency (%)
C1	284.30	10.00	94.77
C2	236.70	10.00	78.90

dc bias and adjusting the tuner. One of the modules (M1) delivers a maximum power of 162 mw at 10 GHz. The maximum power output of the other module (M2) is found to be 138 mw at 10 GHz. The difference in power outputs implies that the two modules are nonidentical.

For cascading M1 and M2, there are two options. On the shortside, it is either M1 or M2. We call the former combination C1 and the latter C2. The maximum power outputs of both C1 and C2 are measured and the measurement setup is same as that for the measurement of an individual oscillator output power and frequency. For these measurements circuit, bias voltage, and the spacing between the mount-pairs have been optimized. The power: combining efficiency (η) of each combiner (C1, C2) is determined from the basic definition [5] that it is the ratio of maximum power output of the power-combiner to the sum of the maximum power outputs of the individual oscillators. The results obtained are summarized in Table I

The experimental results (Table I) show that with the higher power module on the shortside, combiner C1 delivers more power output than combiner C2 which has the higher power module on the output side. The same two modular structures form the combiners of C1 and C2. The wall losses in the two cases are therefore same. Furthermore, both C1 and C2 circuits are optimized for maximum power outputs. Thus, considering the results of theoretical analysis (Section II), the excess power loss in C2 (16% more than C1) can be attributed to larger reflection between the two mount pairs. The 95% Power-combining efficiency of C1 shows that a cascade of nonidentical double-diode oscillator modules can be a reasonably good power-combiner, provided the modules are placed in the proper order.

IV. CONCLUSION

Theoretical and experimental studies of cascaded nonidentical double-diode waveguide oscillator modules lead to the conclusion that such a composite structure can be a power-combiner of useful power-combining efficiency. An important design requirement is that between two adjacent modules, the higher-power one should be on the short-side. If this condition is not satisfied, severe power reflection between the mount-pairs of the two modules may lead to considerable loss in power-combining efficiency.

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