Network Analysis of Planar Spatial Power Combining

Tatsuo Itoh
Dept. of Electrical Engineering
University of California, Los Angeles
Los Angeles, CA 90024-1594

ABSTRACT

Planar multiple-device power combining fundamental and harmonic oscillators based on the periodic structure are presented. A small signal analysis based on a network theory leading to the design of such oscillator is described. A large signal analysis based on a new voltage-frequency updating method is used for characterizations of typical configurations.

1. INTRODUCTION

As the frequency of operation is increased, output power from any solid state device tends to decrease. In order to achieve a meaningful amount of power, a power combining is a remedy [1]. At millimeter-wave frequencies and beyond, the loss in the waveguide structures increases. Thus the spatial power combining becomes attractive [2]. More recently, the integrated circuit technology has been advanced in such a degree that many millimeter-wave circuits can be built in an integrated circuit form. In addition to typical advantages of the integrated circuits, its open nature can be used for an additional benefit. The radiating function can be incorporated directly so that a component that can be used in a quasi-optical system can be developed. Several examples of such circuits have been reported [3,4]. In addition, it is often more advantageous to generate a harmonic directly from a planar oscillator, because most solid state devices exhibit nonlinearity in addition to negative resistance [5].

This paper deals with the modeling aspect of a planar periodic power combining oscillator. In its original form this is a planar integrated circuit version of the single cavity multiple-device Kurokawa oscillator [6]. However, due to its open nature, it can be used for a quasi-optical power combining. In what follows, the structure and operating principle are briefly described. This is followed by a simple application of the eigenvalue equation for operation according to Kurokawa. Finally, a new voltage-frequency update method [7] will be applied to a typical power combining oscillation.

2. STRUCTURE AND OPERATING PRINCIPLE

Fig.1 shows a typical configuration of the periodic power combining oscillator. In this particular example, Gunn diodes are used for circuit demonstration at X band, although different types of devices such as QWITT are likely to be used at higher frequencies. In Fig.1, the inductive stub essentially resonates out the shunt capacitance of the device which is assumed to be expressed as a parallel combination of such capacitance and a negative resistance. The equivalent circuit for this structure is shown in Fig.2. If one chooses the distance d equal to one half of guide frequency, this periodic structure falls into the surface wave stopband region so that the devices are mutually locked in the oscillation. On the other hand if the spacing between the devices is one guide wavelength, the periodic structure falls into the leaky wave stopband so that the oscillation signal radiates into the broadside direction. Hence, if the multiple-device oscillator oscillates at the frequency corresponding to the surface wave stop band, and subsequently generates the second harmonic due to nonlinearity in the device, then the second harmonic coincides with the leaky wave stop band, provided that the dispersion of the connecting transmission line is negligible. Since the phases of the second harmonic at each device are identical, the radiating beam is in the broadside direction. Fig.3 shows an example of such a harmonic space combiner.

3. EIGENVALUE EQUATIONS FOR PERIODIC STRUCTURES

The theory developed by Kurokawa [6] and Peterson [8] can be applied to the structure under discussion here. For an N element construction, the impedance matrix seen from the device ports can be described by the elements z_{ij} (i, j = 1,..., N). The modes of operation can be identified by finding the eigenvalues and the eigenvectors of this impedance matrix. In the case where the spacing between the devices loading the transmission line periodically and the periodic structure is terminated by a load R as shown in Fig.2, z_{ij} can be derived readily from the network analysis. The problem of interest is the case where the periodic structure falls into the stopband region. In the case of the surface wave stopband, only resistive load appearing in this network is R in the figure. Since the electrical length of each period is one half of the wavelength, the impedance matrix becomes

$$Z = R\begin{bmatrix} 1 & -1 & 1 & -1 & . & . & . \\ -1 & 1 & -1 & 1 & . & . & . \\ 1 & -1 & 1 & -1 & . & . & . \\ -1 & 1 & -1 & 1 & . & . & . \\ . & . & . & . & . & . & . \end{bmatrix} \qquad (1)$$

There are N eigenvalues and N eigenvectors. However, all but one eigenvalues are zero. The nonzero eigenvalue is NR. This means that at the fundamental frequency only one mode oscillates because all device ports are short circuited for all other N-1 modes. For the nonzero mode, the oscillation condition is satisfied if one chooses R such that

$$R = -Z_{device}/N \qquad (2)$$

This is the usual oscillation condition. On the other hand, the structures with distributed loads such as those shown in Fig.3, the impedance matrix for the fundamental oscillation is obtained by replacing R in (1) with Z_{in}/N where Z_{in} is the input impedance of the patch structure at the connecting point to the device. Therefore, once again only one mode has nonzero eigenvalue and the oscillation condition for this mode is

$$Z_{in} = -Z_{device} \qquad (3)$$

For the second harmonic oscillation, the period between the devices becomes one full wavelength so that the electrical length is 2π. Therefore all the elements in the impedance matrix become unity. Once again, only one mode has a nonzero eigenvalue for which the oscillation condition is given by (3) except that both sides of the equation need to be evaluated at the second harmonic frequency. The discussions presented in this chapter do not provide information at frequencies other than the design frequency.

4. LARGE SIGNAL MODELING

In the periodic power combining oscillator such as those presented above, the coupling of the devices is very strong. Hence, the ability to self-lock to each other cannot be correctly predicted by the weakly coupled formulation by Adler. Although the eigenvalue analysis developed by Kurokawa [6] is useful for finding the modal behavior of the configuration, it does not include the effect of higher harmonics and assumes that the large signal device impedances are a function of amplitude only.

In the present paper, the voltage-frequency update method developed in [7] is applied to the periodic power combining oscillators. Since the three types presented above operate essentially on the same mechanism, the one shown in Figs.1 and 2 are used for modeling here. However, before presenting a specific application, the basic procedure in [7] is given, although the details are left in [7].

In this method, the harmonic balance equation is solved consistently by means of the modified relaxation technique. The voltage across each port joining the passive and active subcircuit is expressed either in terms of the time series or the Fourier spectrum. This voltage applied to the device side provides the current at the joining port. The current is then applied to the passive subcircuit to find the updated voltage. In updating the voltage, we use a relaxation method with appropriate relaxation constant. This technique is quite standard in many amplifier analysis techniques [9]. In the case of free-running or self-locking oscillators, the oscillation frequency is another unknown. Therefore, the frequency must also be updated in a relaxation process. This is introduced in [7].

The structure to be analyzed has two resonant mechanisms. At the each device terminal, an inductive stub is attached to nullify the shunt capacitance of the device. This arrangement makes the device impedance purely resistive to satisfy the oscillation condition in (2). In addition, the half wave spacing between the devices provides another mechanism for resonance. In the example of calculation, it is assumed that the X band Gunn diode rated for 10 mW output follows a simple cubic law of $i = -0.01v + 0.0015\,v^2 + 0.001v^3$. The device capacitance is assumed to be 0.4 pF. The transmission line used is a 50 Ω microstrip line. In the calculations, a total of twelve harmonics is used. The device resonance determined by the device capacitance and the inductive stub is varied in the test calculations. It is found that as the number of diodes is increased, the importance of the periodicity decreases in comparison with the individual device resonances. When the deviation of the device resonance from the half wave frequency of the periodic structure, no convergent solution can be found and hence the diodes do not lock to each other any more.

The output power from the power combining oscillator is studied as a function of the device resonance. It is found that the output power increases as the device resonance is tuned away from the half wave frequency of the periodic structure. The degree of power increase is more pronounced as the number of diodes is increased from 2 to 4. Since the environment to each device changes as the frequency is detuned, the power generated from individual devices can be different.

5. CONCLUSIONS

A simple design rule for a number of power combining oscillators based on the periodic structure is presented. A new voltage-frequency updating method is used for characterizing the large signal operation of these oscillators.

ACKNOWLEDGMENT

The work reported here was supported by Army Research Office Contract DAAL03-88-K-0005. The author acknowledge the numerical and experimental effort expended by former graduate students, A. Mortazawi and H. D. Foltz at The University of Texas at Austin.

REFERENCES

[1] K. Chang and C. Sun, "Millimeter-wave power combining techniques," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-31, No.2, pp.91-107, February 1983.

[2] J. W. Mink, "Quasi-optical power combining of solid-state millimeter-wave sources," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-34, No.2, pp.273-279, February 1986.

[3] J. Birkeland and T. Itoh, "FET-based planar circuits for quasi-optical sources and transceivers," IEEE Trans. Microwave Theory and Techniques, Vol. 37, No.8, pp.1452-1459, August 1989.

[4] A. Mortazawi and T. Itoh, "A periodic planar power combining oscillator," IEEE Trans. Microwave Theory and Techniques, Vol. 38, No.1, pp.86-87, January 1990.

[5] A. Mortazawi and T. Itoh, "A periodic second harmonic spatial power combining oscillator," 1990 IEEE MTT-S International Microwave Symposium Digest, pp.1213-1216, May 1990, Dallas, TX.

[6] K. Kurokawa, "The single-cavity multiple-device oscillators," IEEE Trans. Microwave Theory and Techniques, Vol. MTT-19, No. 10, pp.793-801, October 1971.

[7] H. D. Foltz, J. H. Davis and T. Itoh, "Voltage-frequency update for nonlinear analysis of free-running and injection-locked multiple-device oscillators," to appear in 1991 IEEE MTT-S International Microwave Symposium Digest, June 1991, Boston, MA.

[8] D. F. Peterson, "Harmonic power combining of microwave solid-state active devices," IEEE Trans. Microwave Theory and Techniques, Vol.MTT-30, No.3, pp.260-268, March 1982.

[9] V. D. Hwang and T. Itoh, "An efficient approach for large-signal modeling and analysis of the GaAs MESFET," IEEE Trans. Microwave Theory and Techniques, Vol.MTT-35, No.4, pp.396-402, April 1987.

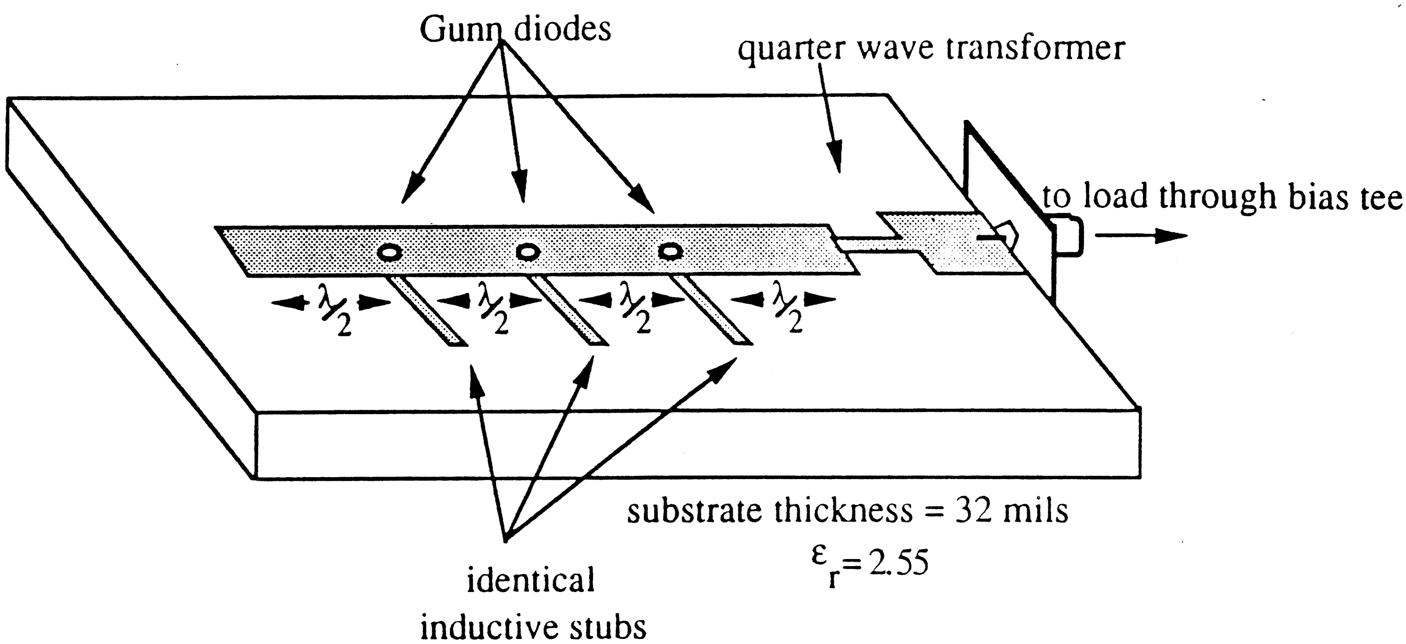

Fig.1 Three diode periodic power combining oscillator

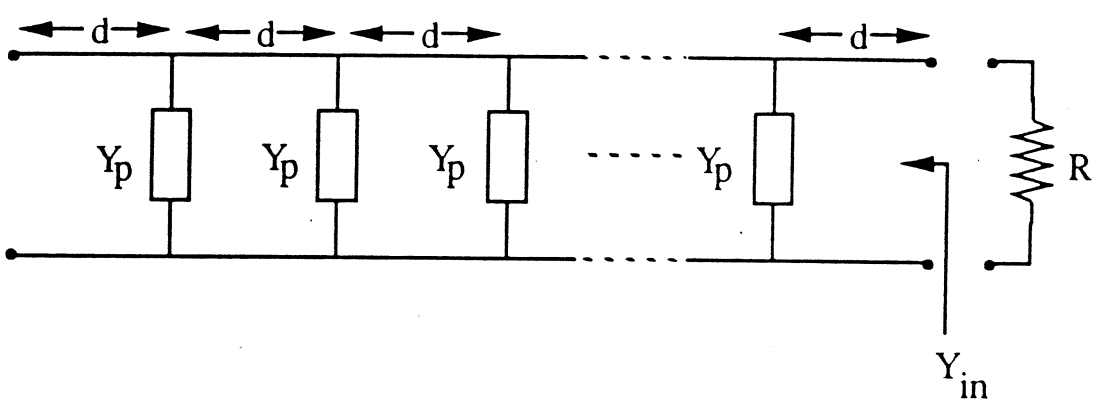

Fig.2 Transmission line loaded periodically with admittance Y_p

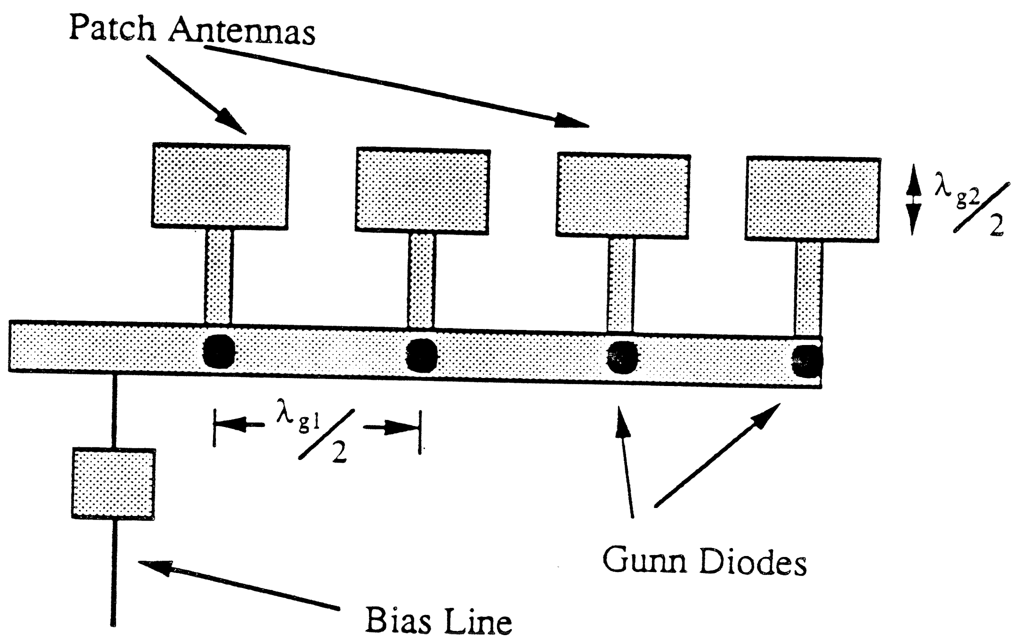

Fig.3 Four diode spatial second harmonic power combiner