ACCURATE ELECTROMAGNETIC CHARACTERIZATION OF QUASI–OPTICAL PLANAR STRUCTURES

P. Arcioni[1], *M. Bozzi*[1], *L. Perregrini*[1], *A. R. Ruiz Laso*[2]

[1] University of Pavia, Dept. of Electronics, Via Ferrata 1, 27100, Pavia, Italy.
Phone +39 0382505200 Fax +39 0382422583 E–mail m.bozzi@ele.unipv.it

[2] University of Cantabria, Av. los Castros s/n, 39005, Santander, Spain.

ABSTRACT – *Quasi–optical planar circuits include large arrays integrated with non–linear devices. Their design requires the modeling of the planar array as well as the characterization of the active devices. In this paper we present a method for the calculation of the voltages induced on the elements of a planar array by the input beam, as well as the evaluation of the array impedance matrix. These parameters, together with the active device modeling, allow for a full characterization of the quasi–optical circuit.*

1. INTRODUCTION

In the recent years, a considerable attention has been devoted to the design and modeling of quasi–optical circuits [1]. They find many applications (mixers, frequency multipliers, amplifiers, *etc.*) in the microwave as well as in the millimeter–wave range. Moreover, they are relatively easy to fabricate, small and light, and represent a very attractive solution for circuits operating in the submillimeter–wave range.

In many millimeter–wave applications, quasi–optical circuits consist of a planar array of antennas on a semiconductor substrate, monolithically integrated with non–linear devices. In order to improve the system performance, it is typically required the use of external filters and of dielectric matching layers (Fig. 1) [2].

The design of a quasi–optical circuit requires, on one hand, the characterization of the active device (Schottky diode, HBV, Gunn diode, *etc.*), and, on the other hand, the electromagnetic modeling of the whole structure, including the planar array, the filters and the dielectric layers.

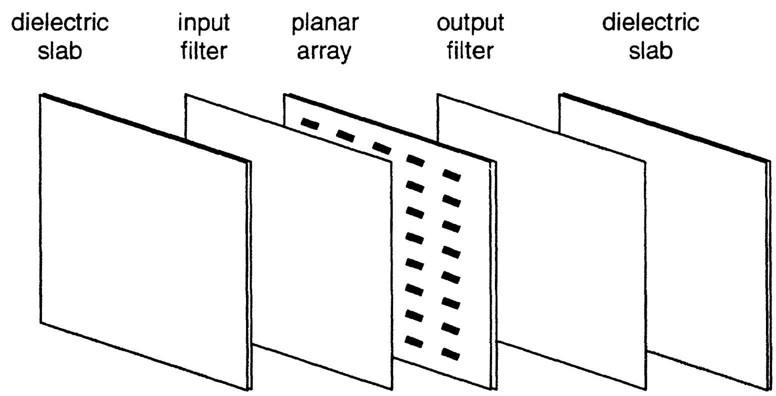

Fig. 1 – Complete setup of a quasi–optical circuit for millimeter–wave applications.

The global modeling provides a multi–port equivalent junction, each port being connected to a non–linear active device (Fig. 2).

Many research groups have been involved in the accurate modeling and characterization of active devices [3,4], achieving an excellent level in the device optimization. On the contrary, less attention has been devoted to electromagnetic issues. The use of commercial software may result not satisfactory, due to the long computation time and, consequently, to a cumbersome optimization process.

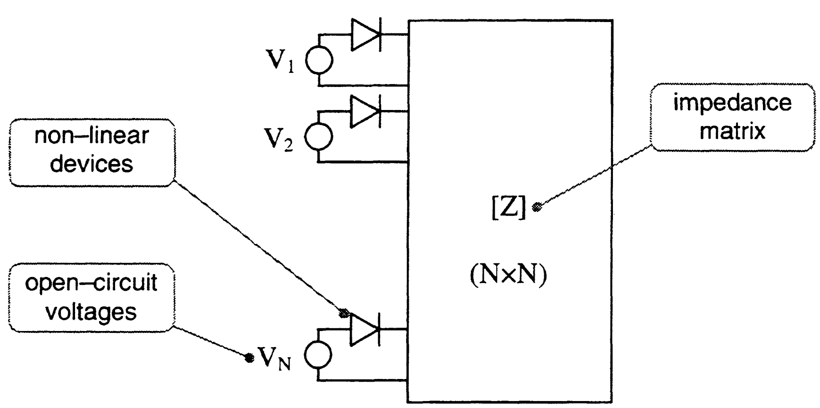

Fig. 2 – Equivalent circuit model of a quasi–optical active circuit.

In this paper, we present a fast and rigorous method for the electromagnetic characterization of the linear part of the quasi–optical circuit. This analysis provides:

i) the voltages induced at the antenna terminals of a planar array by the input beam (typically gaussian);

ii) the impedance matrix of the planar array.

This approach is very efficient from a computational point of view, since the calculation of both the voltages and the impedance matrix can be reformulated under the infinite array approximation. Moreover, the algorithm is very flexible: the array geometry, as well as the position and characteristics of filters and dielectric layers, can be given arbitrarily.

2. CALCULATION OF THE VOLTAGES

For the calculation of the voltages induced at the antenna terminals, we consider an input beam with a gaussian transverse distribution on the plane of the array (Fig. 3). This hypothesis well represents a typical setup of quasi–optical structures, where the field radiated by a horn is focused on the array by a system of mirrors.

Even if the array has a finite transverse dimension, the incident field effectively illuminates only a portion of the array: as a consequence, from an engineering point of view, the edge effects can be completely neglected and the array can be considered as an infinite array.

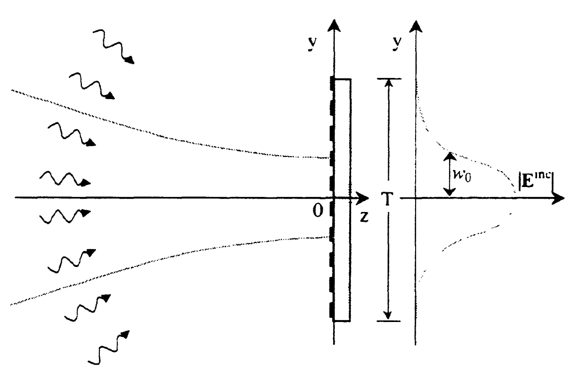

Fig. 3 – Planar array exited by a gaussian beam.

In order to calculate the voltages induced on the array elements, the incident gaussian field $\mathbf{E}^{inc}$ can be approximated by the combination of a set of uniform plane waves incident from different directions

$$\mathbf{E}^{inc}(x,y,z) = \sum_{m,n=-N}^{N} \mathbf{F}_{mn} e^{j(\kappa_{x_m} x + \kappa_{y_n} y)} e^{-\gamma_{mn} z} \tag{1}$$

where

$$\mathbf{F}_{mn} = \frac{A\pi w_0^2}{T^2} e^{-\frac{w_0^2(\kappa_{x_m}^2 + \kappa_{y_n}^2)}{4}} \left(\mathbf{u}_y + j\frac{\kappa_{y_n}}{\gamma_{mn}} \mathbf{u}_z \right) \tag{2}$$

$$\kappa_{x_m} = \frac{2\pi}{T} m = k \sin\vartheta_{mn} \cos\varphi_{mn} \tag{3}$$

$$\kappa_{y_n} = \frac{2\pi}{T} n = k \sin\vartheta_{mn} \sin\varphi_{mn} \tag{4}$$

$$\gamma_{mn} = \sqrt{(\kappa_{x_m}^2 + \kappa_{y_n}^2) - k^2} \tag{5}$$

Moreover, $k = \omega\sqrt{\varepsilon\mu}$ is the wave–number at the operation frequency, $(\vartheta_{mn}, \varphi_{mn})$ represents the direction of the (m,n)–th incident plane wave, T is the transverse dimension of the array and A and w_0 are the amplitude and the beam waist of the incident gaussian field, respectively.

Each plane wave determines a periodic excitation of the array. Therefore, due to the periodicity of the array and of the excitation field, the calculation of the voltages induced on all the array elements by each plane wave can be performed under the infinite array approximation. With this assumption, the analysis of the array reduces to the investigation of a single unit cell (Fig. 4).

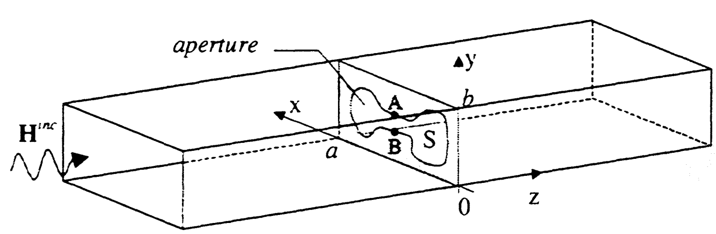

Fig. 4 – Elementary cell of the array.

The elementary cell of the array is a rectangular waveguide with periodic boundary conditions [5]. It includes a metal screen, with an arbitrarily shaped aperture, and (possibly) a layered medium stratified along with the z direction. The layered medium inside the waveguide accounts for the presence of filters and dielectric slabs.

The aim of the work becomes the calculation of the partial voltages $V_{\alpha\beta}^{mn}$, due to the single plane wave (m,n) on a generic array element (α,β). These voltages have the same amplitude on all the array elements and a periodic phase shift depending on the angle of incidence of the plane wave and on the position of the element in the array.

The analysis of the unit cell is based on the equivalence theorem and on an integral representation of the fields. The resulting integral equation is solved by the Method of the Moments [6].

Once the partial voltages induced by all the plane waves on the unit cell have been computed, the total voltages on all the array elements can be obtained using the superposition of the effects.

In such a way, we reduce the calculation of the voltages on all the array elements to the solution of a number of "small" problems (one for each plane wave used in the gaussian beam representation).

3. CALCULATION OF THE IMPEDANCE MATRIX

The method applied in the calculation of the impedance matrix is similar to the one previously presented for the evaluation of the voltages.

In the case of an array, the generic element of the impedance matrix is defined as

$$Z_{ij} = \left.\frac{V_i}{I_j}\right|_{I_k=0\ \forall k\neq j} \tag{6}$$

where I_j is the test current applied to the terminals of the j–th element of the array—being all the other elements open circuited—and V_i is the voltage induced by the same current on the i–th element.

The test current I_j is defined on a narrow strip, connecting the terminals A–B. We observe that it is possible to represent the filament of current on a single cell as a summation of a finite number of periodic excitations

$$I_j(x,y) = \sum_{m,n=-N}^{N} I_j^{mn}(x,y) = \sum_{m,n=-N}^{N} G_j^{mn} e^{j(\kappa_{x_m} x + \kappa_{y_n} y)} \tag{7}$$

Each current I_j^{mn} is periodic and defined on all the elements of the array. Therefore, the infinite array approximation can be applied, and the problem reduces to the investigation of a single unit cell of the array. The aim of the work, in this case, is the calculation of the voltage V_i^{mn} on the i–th element of the array, due to the impressed current I_j^{mn}. As shown in the previous section, the voltages on all the elements can be deduced from the voltages on an element taken as a reference. In fact, all these voltages have the same amplitude, and a periodic phase shift depending on the position of the element in the array.

The calculation of these voltages is based on an integral method, and is exploited using the Method of the Moments [7]. Once the voltages due to all the excitation currens have been calculated, the voltage V_i is found by the superposition of the effects.

4. CONCLUSIONS

The approach we present in this paper is very efficient, from a computation point of view. In fact, the analysis of a finite array with a non–uniform excitation is reduced to a number of "small" analyses, each performed under the infinite array approximation.

Furthermore, this method is very flexible, since the array geometry, the shape of the antennas and the characteristics of the layered medium (filters, slabs) can be given arbitrarily.

This algorithm has been implemented in a Fortran code, which represents a useful CAD–tool for the analysis and the design of quasi–optical structures, e. g. frequency multipliers [8].

5. ACKNOWLEDGEMENTS

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