Single-Substrate Integration Technique of Planar Circuits and Waveguide Filters

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***Abstract*—The integrated planar technique has been considered as a reliable candidate for low-cost mass production of millimeter-wave circuits and systems. This paper presents new concepts that allow for a complete integration of planar circuits and waveguide filters synthesized on a single substrate by means of metallized post (or via-hole) arrays. Analysis of the synthesized integrated waveguide and design criteria are presented for the post pitch and diameter. A filter design method derived from a synthesis technique using inductive post is presented. An experimental three-pole Chebyshev filter having 1-dB insertion loss and return loss better than 17 dB is demonstrated. Integrating such planar and nonplanar circuits on a substrate can significantly reduce size, weight, and cost, and greatly enhance manufacturing repeatability and reliability.**

***Index Terms*—Hybrid integrated circuits, millimeter-wave filters, substrate integrated waveguide.**

I. Introduction

THE past decade has witnessed a rapid development of commercial millimeter-wave wireless systems such as local multipoint distribution service (LMDS) and advanced collision-avoidance sensor. Design and manufacturing costs of such systems are probably the most critical issue in the assessment of their commercial vitality. Integration of active and passive components made of the rectangular waveguide generally requires transitions from planar to nonplanar circuits. Various approaches to solving this problem have been proposed that yield some complex mounting structures [1]–[3]. High-precision mechanical adjustment or a subtle tuning mechanism is needed to obtain good performance for mass production. A planar microstrip circuit often needs to be cut into a specific shape, which is hard to realize in the millimeter-wave range. Furthermore, rectangular-waveguide components are voluminous and expensive to manufacture, which inevitably make the planar/nonplanar integration bulky and costly.

Recently, the concept of the integrated rectangular waveguide has been proposed [4] in which an "artificial" waveguide is synthesized and constructed with linear arrays of metallized via-holes or posts embedded in the same substrate used for the planar circuit. This waveguide can also be realized with complete metallized walls [5], [7], [8]. Several transitions have been proposed [5]–[8] to excite the waveguide. In all these structures, the planar circuits, such as a microstrip line or coplanar waveguide, and the rectangular waveguide are built onto the same substrate and the transition is formed with a simple matching geometry between both structures.

In order to demonstrate the full potentials of the integrated-waveguide scheme, low-loss passive components should be studied and developed. A number of components using the post-wall waveguide technique combined with a metallic layer were analyzed and simulated previously in [9]. Good results were reported for T-junction and isolation performance between waveguides. However, the realization of a low-loss filter without tuning needs to be demonstrated. Planar filters have already been investigated [10], [11] using the concept of electromagnetic bandgaps (EBGs). However the EBG structure is not necessary to design high-Q filter and only one row of via with the concept of an equivalent waveguide can be used. This paper presents the design and performance of the integrated-waveguide filter. We begin with a parametric analysis of the synthesized integrated waveguide. Design criteria are presented for the post pitch and diameter in terms of the maximum dimension ratio. A filter design technique is presented with self-consistent inductive posts that are embedded along the waveguide section. It is shown that integrating the two dissimilar structures on a single substrate allows the design of planar circuits and waveguide filter without resort to tuning or usual mechanical mounting.

II. Integrated-Waveguide Analysis

Judging from its electrical performance, the synthesized integrated waveguide is a good compromise between the air-filled rectangular waveguide and planar circuit [6]. A schematic view of the integrated waveguide is shown in Fig. 1. This waveguide is composed of two parallel arrays of via-holes, delimiting the TE_{10} wave propagation area, as its cutoff frequency is only related to the width "c" of the waveguide as long as the substrate thickness or waveguide height "h" is smaller than "c." The parameter "c" between the two arrays determines the propagation constant of the fundamental mode, and parameters of via-holes "d" and "p" are set to minimize the radiation loss as well as the return loss.

In order to ensure that the synthesized waveguide section becomes radiationless or free from leakage loss, parametric effects of "p" and "d" should be studied. A full-wave finite-element method (FEM) based a commercial software package (HP-HFSS) is used to carry out our simulations.[1] Fig. 2 shows the influence of the pitch length "p" on the loss for diameter "d" with four posts. The other parameters are $c = 5.567$ mm, $h = 0.508$ mm, and $\varepsilon_r = 2.2$. Since we do not consider the

Manuscript received September 15, 2001; revised May 15, 2002. This work was supported by the Natural Sciences and Engineering Research Council of Canada and by the Canadian Institute for Telecommunications Research.

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Digital Object Identifier 10.1109/TMTT.2002.807820

[1] *Agilent HFSS ver. 5.6*, Agilent Technol. Inc., Palo Alto, CA.

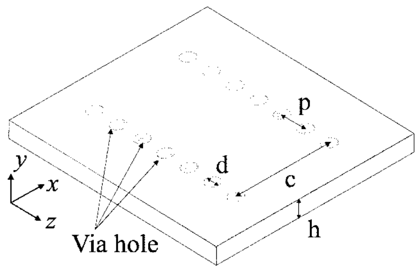

Fig. 1. Configuration of the on-substrate integrated waveguide synthesized using metallized via-hole arrays.

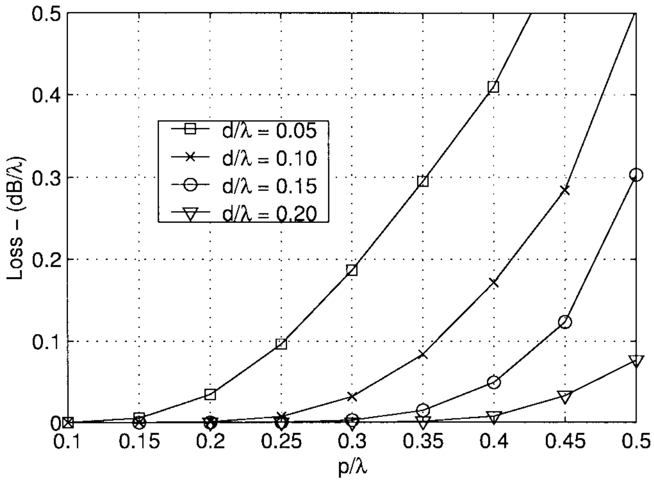

Fig. 2. Normalized insertion loss of the integrated waveguide with respect to the pitch length normalized to the wavelength.

dielectric and conductor losses in the simulations, the loss solely comes from the radiation. All the values are normalized by the wavelength in the dielectric material. These curves indicate that the pitch must be kept small to reduce the loss between adjacent posts. However, the post diameter is also subject to the loss problem. As a result, the ratio d/p is considered to be more critical than the pitch length because the post diameter and pitch length are interrelated. For an electrically small post ($d < 0.2\lambda$), the radiation loss is lower than 0.008 dB/wavelength with a ratio d/p of 0.5. The loss tends to decrease as the post gets smaller for a constant ratio d/p, which is conditioned by the fabrication process.

The synthesized integrated waveguide can no longer be regarded as a normal homogeneous waveguide, and it is, in fact, an artificial periodic waveguide. Therefore, the post diameter may significantly affect the return loss of the waveguide section in view of its input port. Fig. 3 shows the return loss of one period (one via) normalized to the wavelength in relation with the post or via diameter "d" normalized to the waveguide width "c." The ratio d/p is kept at 0.5 in the calculations. To obtain good results in terms of the return loss in the waveguide section, the choice of the via diameter must follow such a design rule as $d/c < 0.4$.

Of course, the above simulations will become inefficient and heavy if a large number of via posts gets involved. To avoid this problem, the synthesized integrated waveguide can simply be modeled by a standard dielectric-filled rectangular waveguide bounded by two parallel metallic walls. To do so,

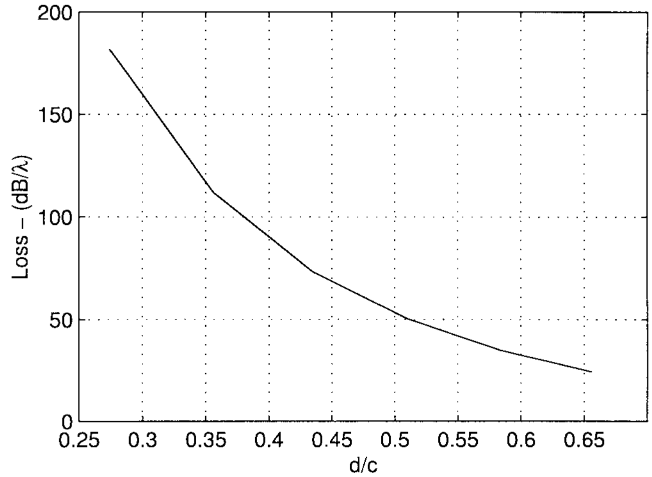

Fig. 3. Normalized return-loss performance of the integrated waveguide as a function of the normalized via diameter.

two integrated waveguides with different lengths are simulated. The phase difference in transmission between the two structures of different lengths allows calculating the propagation constant. This can then be mapped or converted to an equivalent rectangular waveguide with complete bilateral walls. With $d/p \geq 0.5$ and $d/c < 0.4$, the mapping is perfect in all the waveguiding bandwidth of interest. Thus, all the existing design procedures and theory developed for the rectangular waveguide are directly applicable to its synthesized counterpart. Nevertheless, dielectric filling effects and geometrical particularity of the synthesized waveguide should be accounted for.

III. Inductive Post-Filter Design

A filter was designed and measured in [7] with metallic walls. This may need high-precision machining, which overcasts the advantage of the synthesized integrated waveguide compared to the rectangular waveguide. To exploit full advantages of the integrated waveguide, a filter is showcased with embedded posts. However, this kind of filter usually requires several posts of different diameter that are normally not available or difficult to realize in the form of conventionally processed via-holes because these via-holes usually have an identical diameter.

A general method is now presented to design a filter based on posts of the same diameter. The method starts with the general filter theory. First, the integrated waveguide is mapped to a rectangular waveguide using the technique explained in Section II. As illustrated in Fig. 4(b), a *PI* network can model a post in rectangular waveguide. The theory developed by Marcuvitz [12] for posts in a waveguide is used to calculate X_a and X_b. This *PI* network is then transformed into a K-inverter using (1) [13]. With this model, filters are designed on the basis of the well-known synthesis techniques for inductive posts in the rectangular waveguide, as described in [13]

$$K = Z_0 \left| \tan\left(\frac{\phi}{2} + \tan^{-1}\frac{X_a}{Z_0}\right) \right|$$
$$\phi = \tan^{-1}\left(\frac{2X_b}{Z_0} + \frac{X_a}{Z_0}\right) - \tan^{-1}\frac{X_a}{Z_0}. \quad (1)$$

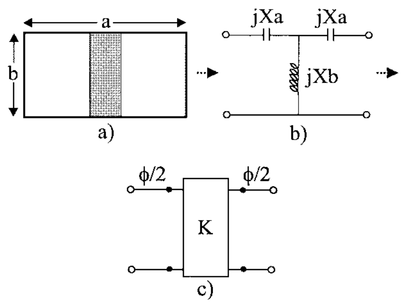

Fig. 4. Design process of inductive post filter. (a) Post in waveguide. (b) Equivalent *PI* network. (c) Equivalent K-inverter network.

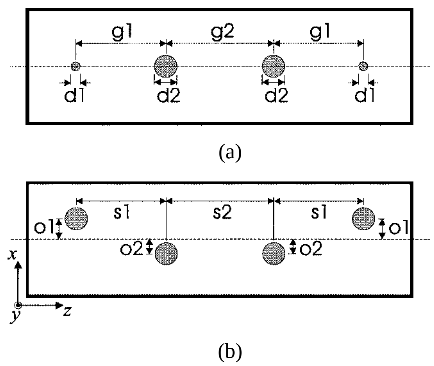

Fig. 5. Topologies of the centered post-filter model with different post diameters and the proposed offset post filter of an identical post diameter.

TABLE I
DIMENSIONS OF THE CENTERED POST-FILTER MODEL WITH DIFFERENT POST DIAMETER AND THE OFFSET POST FILTER OF IDENTICAL POST DIAMETER DESIGNED WITH 0.77-mm VIA

Centered Post filter model			
d1 (mm)	*g1 (mm)*	*d2 (mm)*	*g2 (mm)*
0.22	4.62	0.77	5.11
Offset Post filter model			
o1 (mm)	*s1 (mm)*	*o2 (mm)*	*s2 (mm)*
1.01	4.71	0	5.11

Generally, an inductive post filter has to use a number of posts of different diameter all centered in the guide. The filter geometry can be replaced by an offset post arrangement with the same post diameter as illustrated in Fig. 5. To set up the equivalence between the two filter structures, a number of simulations are made to extract the position of equivalent posts in the offset case.

IV. EXPERIMENTAL RESULTS

With the method presented in Section III, a three-pole Chebyshev filter of 1-GHz bandwidth centered at 28 GHz has been designed, fabricated, and measured. The circuit is constructed on a 0.787-mm-thick dielectric substrate with $\varepsilon_r = 2.2$ (RT/Duroid 5880). It has been shown that a Q factor higher than 500 can be obtained with this substrate [14]. The dimensions of structure referring to Fig. 1 are selected as $c = 5.563$ mm, $p = 1.525$ mm, $h = 0.787$ mm, and the post diameter $d = 0.775$ mm. In order to measure the filter, microstrip transitions are designed as described in [5]. The dimension of the transition, referring to Fig. 1 in [5], are $w = 0.762$ mm, $d = 1.499$ mm, and $l = 1.930$ mm.

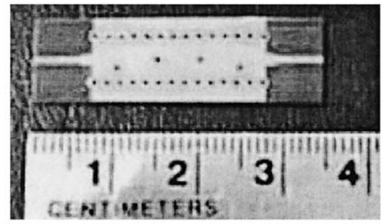

Fig. 6. Photograph of the manufactured three-pole filter with two microstrip transitions.

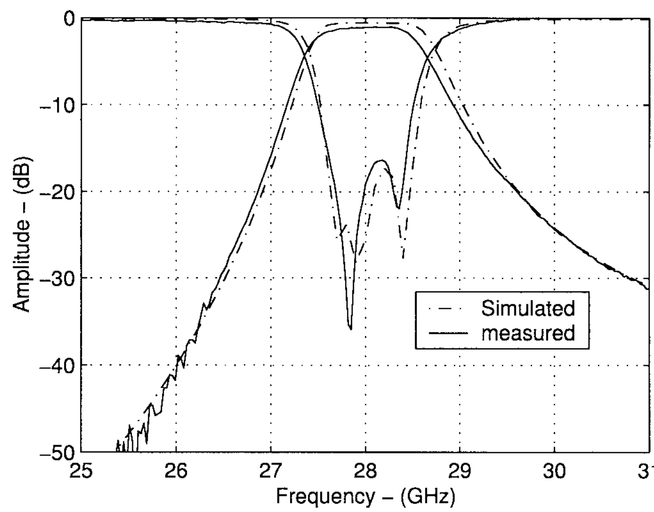

Fig. 7. Measured and simulated results for the new three-pole Chebyshev filter of offset inductive posts with two transitions of microstrip to integrated waveguide.

Table I summarizes dimensions of the centered post-filter model, as well as the offset post-filter design with a diameter of 0.775 mm. The manufactured prototype of the filter is shown in Fig. 6 and the HFSS simulated and measured filtering results are shown in Fig. 7. In the passband, the whole insertion loss is 1 dB and the return loss is better than 17 dB, which indicate an excellent performance for this proposed planar approach. The simulated results, based on the rectangular waveguide model, agree well with the measurements. The conductor losses were not modeled in the simulation since the commercial package used is not accurate for small thickness conductor. This explains the difference between simulated and measured results in the passband.

V. CONCLUSION

New concepts of synthesized waveguide integrated components with planar circuits on a single substrate have been proposed and discussed. Design-oriented analysis of the integrated waveguide has been presented, showing interesting properties. In addition, it is found that a carefully synthesized structure can effectively be replaced by a rectangular waveguide without much difference. Featuring direct integration, small size, and low loss, this new design platform is well suited for a low-cost planar circuit design at millimeter-wave frequencies. To demonstrate the proposed single-substrate hybrid planar/nonplanar technique, a new three-pole filter of 28 GHz with inductive posts has been designed, fabricated, and measured. The simulated and measured results show that this type of filter can be constructed without tuning. The proposed techniques can be used to integrate passive waveguide components with active microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs) for low-cost mass production without any additional mechanical assembling or tuning.

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Dominic Deslandes (S'01), photograph and biography not available at time of publication.

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