AN EXPLICIT DESIGN TECHNIQUE FOR WIDEBAND COUPLERS AND HIGH QUALITY FILTERS USING PERIODIC TOPOLOGY

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ABSTRACT

A novel approach is introduced for computer-aided design (CAD) of wideband couplers and high-quality filters using periodic structures. This design technique consists of two explicit steps. The first step is to obtain single periodic cell parameters for a given electrical specification or vice-versa by the use of field-theoretical approaches in conjunction with the Floquet's theorem. The next step is to determine number of the given periodic cell used in wideband couplers or high-quality filters for a desirable coupling or filtering characteristic. Theoretical and experimental results are presented for non-uniform planar periodic coupler and filter, which are found to be in good agreement. Some interesting features of lossy and lossless periodic structures with finite number of cells are discussed.

INTRODUCTION

With increasing exploitation of monolithic (hybrid) microwave integrated circuits (M(H)MICs), there has been growing interest in applications of planar periodic circuits to wideband couplers and high-quality filters. This is because periodic structures present some distinct properties in comparison with uniform transmission lines, namely, slow-wave propagation and cutoff resonance phenomena related to bandpass and stopband in these types of structures. As reported in [1], these properties can be used in the design of wideband couplers and filters using large number of cascaded miniature periodic cells. Although some applications of periodic or quasi-periodic topologies to wideband couplers were reported [2, 3], there is little or limited information available so far on design aspect of these circuits. In particular, most of these applications considered solely phase compensation over desired bandwidth using periodic topology (for example zigzag structures) while excellent phase equalization over very large bandwidth between odd and even slow-wave modes of miniature periodic circuits is generally ignored in the analysis and design. Moreover, applications of these circuits to high-quality filters remain to be addressed. In general, an efficient and accurate design/synthesis approach is required to fully exploit attractive features of periodic circuits.

Conventionally, design and synthesis of most couplers and filters reported so far are based on the equivalent network theory in conjunction with circuit transformation and lumped parameters [4, 5]. These CAD tools are widely used today and are able to provide fairly accurate results, especially for quasi-TEM transmission lines. However, design and synthesis of periodic couplers and filters become extremely complex by the fact that periodic cells have non-uniform and/or discontinuity-type geometry. It is thus difficult or even impossible to build up an equivalent lumped network (for example, slot-line types). Furthermore, some conventional design concepts are not valid. To name an example in the design of branch-line hybrids and parallel-line couplers, backward arises from the difference between the odd- and even-mode characteristic impedances of the coupled lines [5, 6]. This argument is difficult to be applied or at least confirmed in the design of the periodic couplers because these is no suitable impedance definition for such lines. On the other hand, large number of periodic cells involved in circuits make it difficult or even non-realistic to use full-wave approach based on the field theory for the design purpose. In this paper, a novel approach is introduced to provide a CAD methodology for the design and synthesis of wideband couplers and high-quality filters using periodic slow-wave structures.

THE EXPLICIT DESIGN TECHNIQUE

It is known that any ideal periodic structure can be conceived as an infinite number of cells which are cascade-connected, and the Floquet's theorem allows to simulate the entire structure by considering only one single cell. In practice, the periodic structures such as couplers and filters have always a finite number of cells. Therefore, the analysis based on the Floquet's theorem may no longer be valid. If a large number of periodic cells is considered in building up circuits of interest, however, the above-mentioned modeling is able to provide fairly accurate results. By our experimental and theoretical experiences, the amount of cells necessary to satisfy approximately the analysis of the Floquet's theorem can be determined only by the criteria that the slow-wave propagation at a particular

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frequency can clearly be observed along this periodic structure with finite number of cells. This principle suggests that electrical characteristics of a finitely periodic structure can accurately be obtained by apply the Floquet's theorem as long as the criteria is satisfied.

Based on the above discussion, a simple design approach is developed for accurate CAD and synthesis of wideband couplers and high-quality filters. This technique consists of two explicit design steps in a comprehensive way, which should be universal for passive components based on periodic geometry. The first step is to obtain single periodic cell parameters for a given electrical specification or vice-versa by the use of field-theoretical approaches in conjunction with the Floquet's theorem. In this case, a periodic structure with assumption of infinite extent is analyzed with a hybrid-mode approach, for example, spectral domain approach or any other applicable rigorous numerical techniques. As a result, phase equalization over desirable large bandwidth of the slow-wave odd- and even-modes and central frequency point are identified for coupled lines with a specific geometry, while for single line, central frequency point and stop/pass bandwidth are obtained. Then, S-matrix can be obtained for these single cell by the use of appropriate hybrid-mode analysis. The next step is to determine how many periodic cells are required for the synthesis of desired coupling or filtering characteristics in wideband couplers or high-quality filters. This can usually be done by simple cascaded matrix method. Coupling coefficient for couplers can be adjusted by adding or reducing number of cells used in the design procedure, to name an example. Although the last step may ignore cross-coupling, the design procedure yields fairly good accuracy in predicting the bandwidth, coupling, filtering characteristics, and frequency range. This can be explained by the fact that cascaded periodic cells with the same geometry share the same central frequency and about the same electrical property if a sufficient amount of cells is used. On the other hand, miniaturized periodic geometry is able to yield high and quasi-constant slow-wave factor (small guiding wavelength) over a large frequency bandwidth. This indicates that possible cross-talks at both ends of the structure can significantly be reduced.

RESULTS AND DISCUSSION

As an example, non-uniform periodic microstrip structures are considered for both coupled and single lines. Sinusoidal topology is chosen so that wideband matching at the input and output is easily achieved owing to its curved intersection. In addition, periodic cell geometry is simply characterized by w_{max}, w_{min} and periodic length p (additional parameter s_{min} is considered for coupled lines) as shown in Fig.1. An additional advantage is that this type of structure may have smaller ohmic losses that its counterpart with rectangular stubs or zigzag triangular cells. This is because the current or field singularity is reduced in the smoothly sinusoidal lines. In general, the 50 Ω input and output standard lines are chosen for facilitating measurements. To validate this novel design approach presented above, both 10 dB coupler and stopband filter are simulated and fabricated using this approach with Duroid substrate (thickness = 0.635 mm and ε_r = 10). Fig.2 shows dispersion characteristics of the slow-wave mode propagating along the single periodic line which is assumed to be infinitely extended. It is found that measurement and simulation have a very good agreement even though a quasi-static modeling of the structure (with HP-MDS simulator) is used. The measurement sample is made of 46 cells for the expected filtering characteristics. This indicates that theoretical prediction for infinite periodic lines yields very good results for couplers and filters with large number of cells involved. This confirms our prediction and the criteria described in the preceding section. By the use of HP-HFSS simulator and cascaded S-matrix method, scattering analysis for single cell and synthesis of whole filtering circuit are completed. The simulation and measurement results, as demonstrated in Fig.3, are found to be in good agreement between 11.3 GHz and 13.8 GHz with 20% bandwidth except some difference for S_{21}. This can be attributed to the lossless structure considered in the simulation. Nevertheless, a high-quality filter with S_{21} (< - 40 dB) is obtained.

Fig.4 shows forward coupling and return loss characteristics over frequency band 3 - 12 GHz. To achieve 10 dB coupling coefficient, 88 periodic cells are required in the design and fabrication of the coupler. It can be seen that a fairly good agreement is achieved between theoretical simulation (HP-HFSS) and experimental results although there is a deviation observed around low- and high-frequencies over bandwidth of interest. It is expected that 3 dB coupler can readily be realized by using miniature dimension (in this example, reducing s_{min}) or strong coupling periodic geometries (not shown in the paper). This can easily be done by MMIC and MHMIC technology.

Trapezoidal periodic cells (see Fig.1c), which are found to be electrically equivalent with the sinusoidal cells in our modeling, are considered to simplify the following analysis. Fig.5 illustrates influence of the number of cells on 3 dB relative bandwidth and central frequency of a stopband periodic filter in the lossless case. These simulation curves indicates that 30 periodic cells are sufficient to characterize an infinite periodic structure with practically constant bandwidth and central frequency. This feature confirms further our criteria of choice with respect to the number of cells required in this implicit design technique. It is expected that there is an optimum point with the minimum loss and number of cells required for a particular stopband filter while f_0 and $\Delta f/f_0$ remain to be constant. And also, they suggest that the parameters f_0 and $\Delta f/f_0$ depends only on the structural dimensions of a single cell and other filtering properties such as return losses etc. are also related to the number of cells used for the filter.

The same phenomenon is also observed in the case of a coupled periodic structure, as shown in Fig.6 except that $\Delta f/f_0$ varies slightly with the number of cells. This may be explained by the fact that increasing the coupling coefficient by adding periodic cells probably causes this little difference. Nevertheless, this presents only 5% deviation for a wideband coupler with total number of cells which varies from 20 to 120. As a matter of fact, this can be ignored in this design technique. However, by considering ohmic losses (Au conductor with a thickness of 5 μm), the relative bandwidth increases quasi-linearly from 70% to 105% with the number of cells while the central frequency decreases subsequently with a difference of 4 GHz. It can be seen that in case of considering losses, the proposed design technique is still valid owing to the linear characteristics of periodic structures with respect to the number of cells. Fig.7 shows the exponential dependence of coupling coefficient with the number of cells used in the coupler. The lossless curve suggests that a 3 dB coupler can easily be obtained by increasing number of cells even though the weak coupling structure is considered. Interestingly, it is impossible to obtain a 3 dB periodic coupler in the presence of losses. To solve this problem, there are two possibilities: the use of strong coupling periodic structures or superconducting periodic topology.

CONCLUSION

A novel approach is presented for CAD and synthesis of wideband couplers and high-quality filters based on periodic topology technology. The design concept effectively combines rigorous analysis of infinite periodic transmission lines and accurate cascaded S-matrix of finite periodic circuits. A criteria is proposed to determine the amount of cells, which is confirmed by results and discussion. Experimental prototypes and theoretical simulations validate the present design approach within satisfactory accuracy for both 10 dB coupler and stopband filter based on non-uniform periodic planar topology. Some interesting properties are also discussed with applications of the proposed technique to periodic filters and couplers. This design technique demonstrates valuable applications of periodic structures in M(H)MICs

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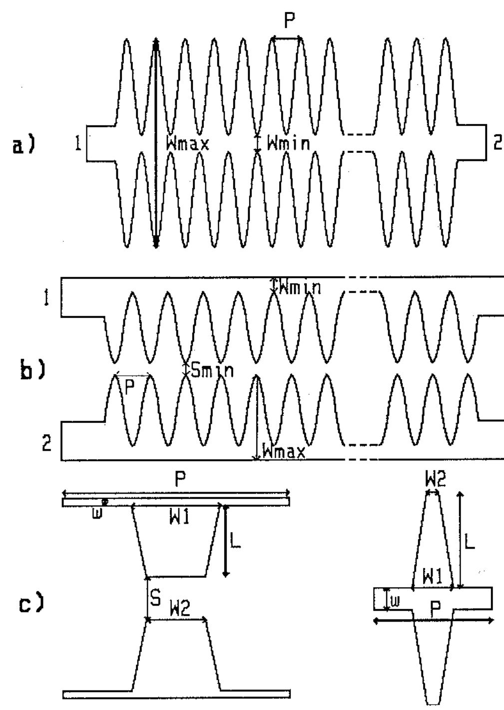

Fig.1: Illustration of wideband couplers and high quality filters using periodic topology (unit: mm).
(a) Sinusoidal periodic filter (w_{min} = 0.6, w_{max} = 7.2, p = 1.0, number of cells = 46).
(b) Sinusoidal periodic coupler (w_{min} = 0.2032, w_{max} = 1.2192, s_{min} = 0.1778, p = 0.508, number of cells = 88).
(c) Trapezoidal periodic cell. (w_1 = 0.15, w_2 = 0.128, w = 0.03 mm, s = 0.18, L = 0.3, p = 0.385) for couplers, and (w_1 = 0.07, w_2 = 0.021, w = 0.13 mm, L = 2.5, p = 0.2) for filters.

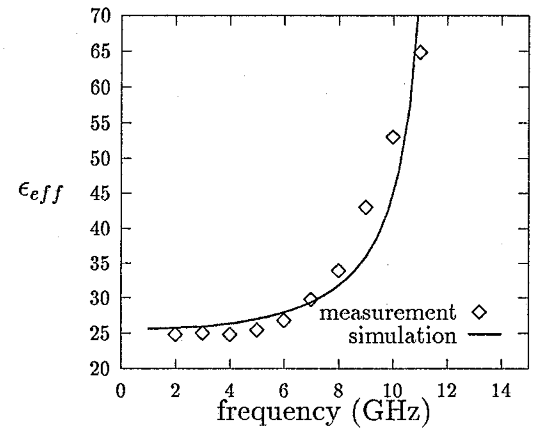

Fig.2: Theoretical and experimental results of a single periodic microstrip lines.

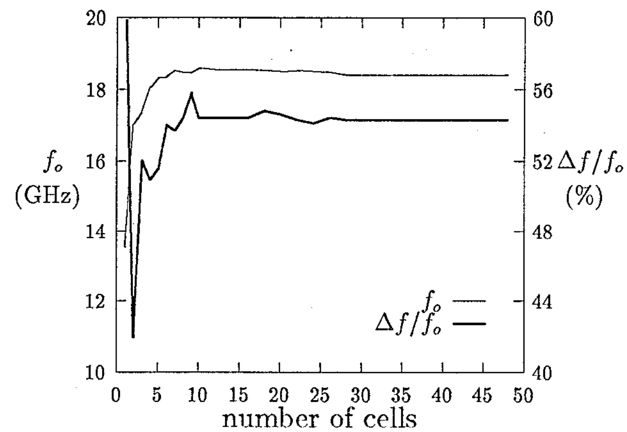

Fig.5: Influence of the number of cells on the 3 dB relative bandwidth and central frequency of a stopband periodic filter.

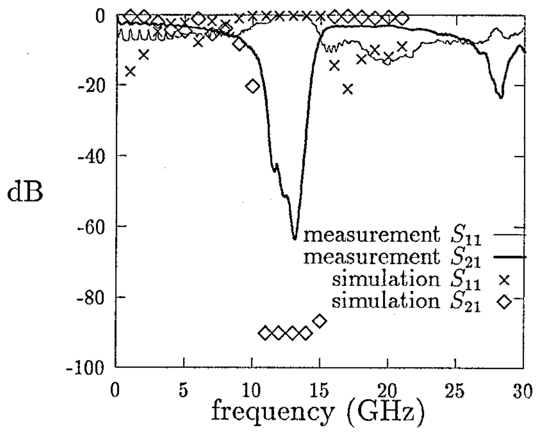

Fig.3: Transmission and reflection characteristics of the high quality filter using periodic tolology technology.

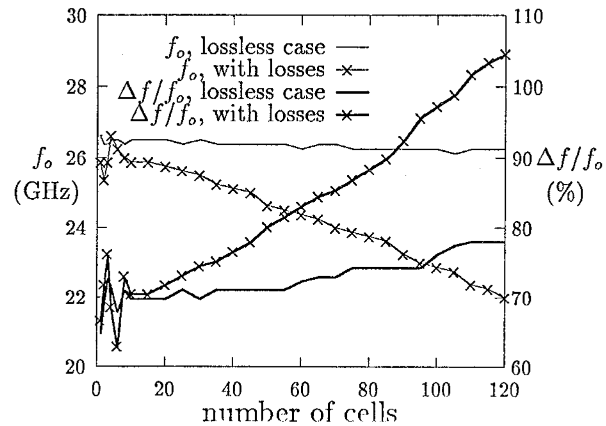

Fig.6: Influence of the number of cells on the 2 dB relative bandwidth and central frequency of a wideband periodic coupler.

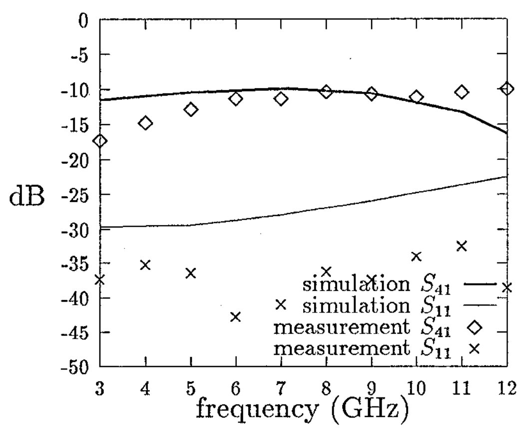

Fig.4: Theoretical and experimental results for coupling and return loss behavior of a 10 dB wideband periodic coupler.

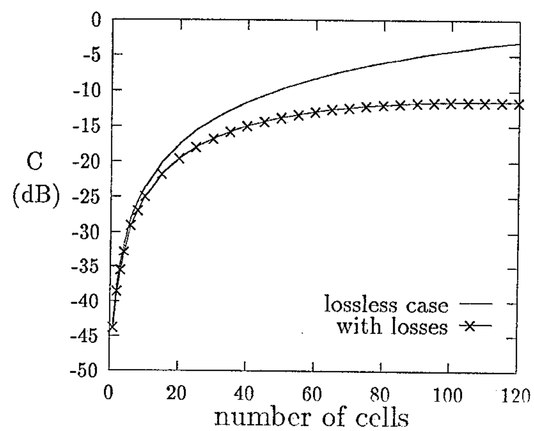

Fig.7: Coupling characteristics of the nonuniform periodic coupler as a function of number of cells.