Toward an Optimum Design of NRD-Guide and Microstrip-Line Transition for Hybrid-Integration Technology

Abdallah Bacha and Ke Wu

***Abstract*— The newly proposed hybrid-integration technology of a nonradiative dielectric (NRD)-guide and planar structure offers an attractive alternative for designing microwave and millimeter-wave integrated circuits and systems. This paper presents an attempt with a transmission-line matrix (TLM) analysis toward accurate design and optimization of the NRD/microstrip-line transitions for the proposed scheme. Electrical performance of the transitions is studied with respect to various parametric effects such as the influence of coupling slot size, NRD and microstrip-line open-ends, as well as dielectric permittivity. Experiments with the designed transitions are made to validate our TLM analysis, as well as to demonstrate good performance. Calculated and measured results suggest that such a hybrid integration have a promising future as one of high-frequency building blocks.**

***Index Terms*—CAD and optimization, hybrid-integration technology, integrated transitions, microstrip line, NRD-guide, TLM algorithm.**

I. INTRODUCTION

Wireless applications at millimeter-wave frequencies stimulate research interests looking for more suitable guided-wave structures than conventional ones. The nonradiative dielectric (NRD)-guide, which was proposed by Yoneyama and Nishida [1], [2], is an attractive transmission medium at these frequencies. Its low-loss transmission and low-cost fabrication present two major advantageous factors for successful commercial applications. Various components and devices, as well as systems, have been made with this technology [2]–[4]. Nevertheless, it is recognized that its integration with active devices and popular planar structures is not so easy [5], [6], although an early unsuccessful attempt was made with a side-coupling scheme using a stripline that is located close to the NRD-guide [7].

To solve this bottleneck problem, a new alternative technique has been recently proposed, which makes use of a slot (or aperture) etched onto the ground plane of a microstrip or coplanar waveguide (CPW) vertically coupled to the NRD-guide (top and/or bottom sides) [5], [6]. This coupling scheme allows developing a multilayer or multiple-level hybrid integration of planar structures and NRD-guides. This new integration technology may combine advantages of these involved dissimilar structures, while inherent shortcomings of each individual building block can be effectively eliminated. Preliminary theoretical and experimental results have indicated the usefulness of the slot-coupling technique [5], [6] and a number of passive and active circuits have been developed with the newly proposed technology [8], [9]. However, the modeling and design of such transitions are still in a very early stage and only an approximate theory (the Bethe's hole-coupling theory) has been applied to characterize electrical performance of the NRD-guide/microstrip-line transitions. In addition, only rectangular slot coupling was featured in [6] and it is known that other irregular slot geometry may yield better performance, as studied for wide-band planar-line-to-planar-line coupling [10]. Therefore, an additional effort should be made to exploit the potential of this new integration technique with various potential coupling aperture topologies. On the other hand, the self-limited approximate model developed in [5] cannot be used to predict very wide slot or irregular slot-coupling scheme between the NRD-guide and microstrip line. A field-theoretical technique has to be developed for accurately modeling and designing the transition [11].

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The authors are with the PolyGrames Research Center, Department of Electrical and Computer Engineering, École Polytechnique de Montréal, Montréal, P.Q., Canada H3C 3A7.

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To this end, a transmission-line matrix (TLM) algorithm has been developed to model this complicated structure. The TLM method [12], [13], like the finite-difference time-domain (FDTD) method, is well known for its capability of handling irregular complex structures as long as the central processing unit (CPU) and random access memory (RAM) of a computer permit. The present algorithm is time-domain-based and uses the well-established symmetrical condensed node [13]. Since the transitions to be simulated are discretized in space with a discrete time consequence, frequency response of the structure is obtained through a simple Fourier transform. Absorbing boundary condition [14] is also required to truncate our unbounded structure. In this case, a simple match-loads scheme is implemented to simulate the absorbing boundary condition.

In this paper, a number of parametric effects are considered in the modeling such as the NRD-guide and microstrip-line open-ends, and coupling slot topologies, etc. Electrical performance of two types of slot (rectangular and bowtie slots) are examined in detail. An attempt is made to design and optimize a transition over 18–22 GHz together with experiments. Good agreement is observed between the theoretical predictions and measured results.

II. ANALYSIS TECHNIQUE

Fig. 1 shows a typical transition structure between the NRD-guide and microstrip line in our case study. The structure consists of a microstrip line deposed on the top of the NRD-guide and both dissimilar structures share the same ground plane. The coupling is achieved through an etched slot or aperture on the ground plane. To excite the desired fundamental longitudinal-section magnetic (LSM) mode from the microstrip TEM mode, the microstrip line should be in the perpendicular position with respect to the NRD-guide, and the coupling slot should be oriented in parallel to the NRD-guide. This arrangement allows one to have a magnetic coupling mechanism, which has been already detailed in [5] and [8]. In our numerical modeling, a complete experimental microstrip-line–NRD-guide microstrip-line topology is simulated with the TLM algorithm.

As for TLM simulation, an orthogonal three-dimensional adaptive mesh is used to enable a good space resolution over the microstrip-line conductor, coupling slot, and NRD-guide open-ends. In addition, an absorbing boundary condition [14] is accommodated in the TLM simulation for defining a computational window of this unbounded structure. Subsequently, a Gaussian-pulsed TEM voltage is applied to the microstrip line and one simulation leads to results for the entire frequency spectrum of interest. To determine S-parameters, reference planes are adequately chosen to have a good separation of the reflected signal from the incident one. The observation planes are located a sufficient distance from the slot such that only the quasi-TEM mode exists in the microstrip line and higher order modes generated by the discontinuities are quickly attenuated. One of the advantages using a time-domain simulator is that it is possible

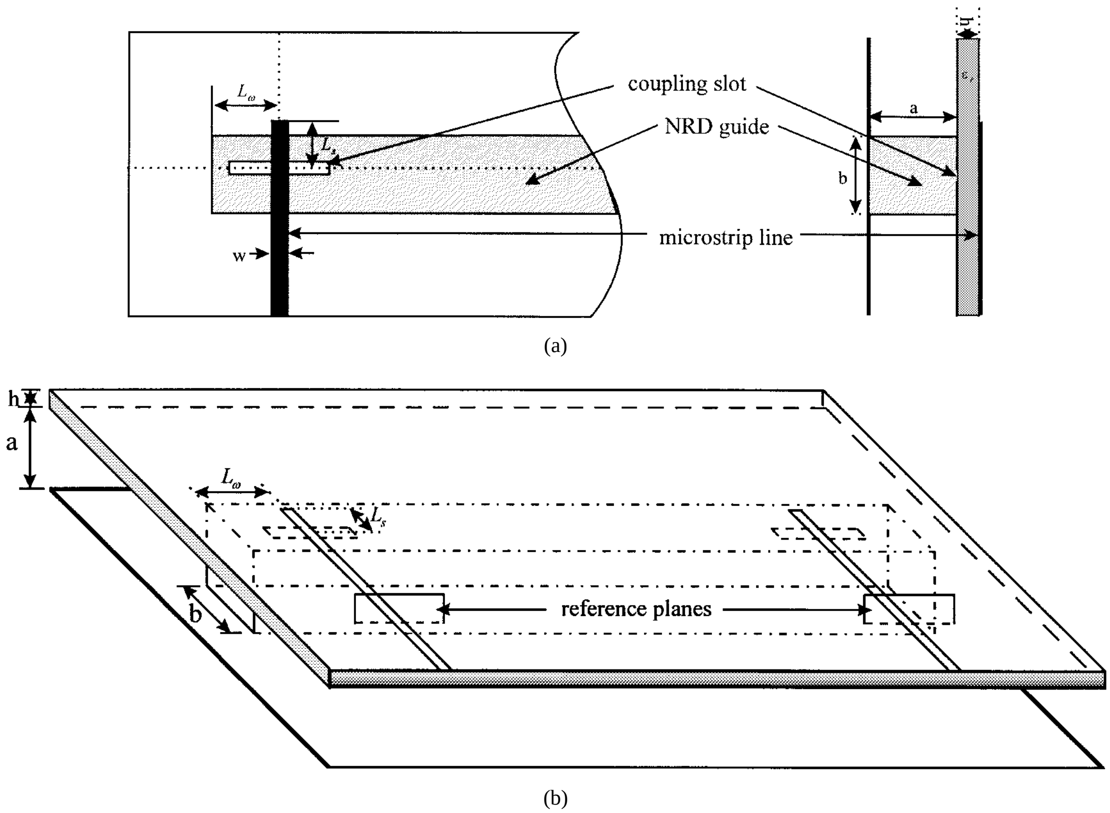

Fig. 1. Illustrative view of (a) geometry and (b) test setup of the transition from microstrip line to NRD-guide.

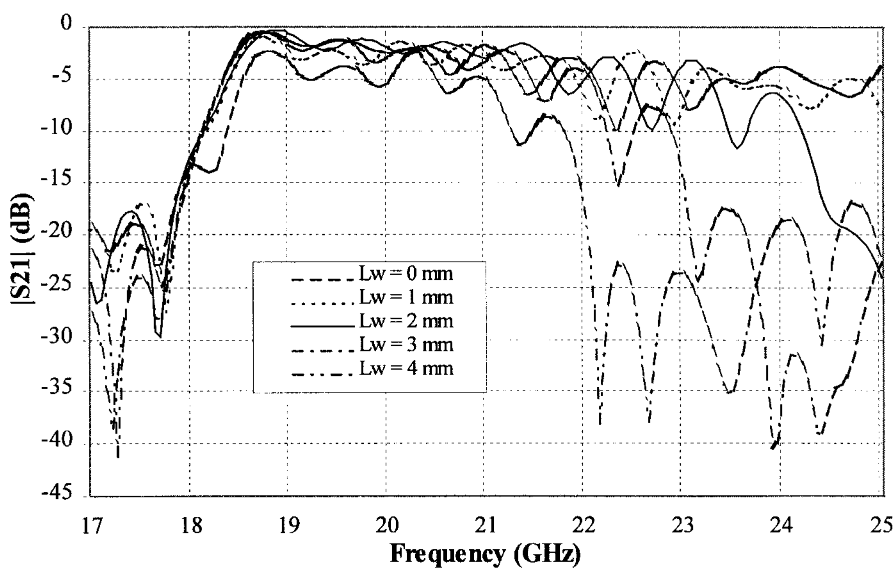

Fig. 2. Bandwidth and transmission performance as a function of the NRD open-end (L_w) with a microstrip-line open-end fixed at $L_s = 3$ mm. A length slot (l) is chosen to be equal to 6.5 mm.

to separate different reflected waves even if the output line is mismatched. The S-parameters are deduced from the reflected and transmitted waves in the two reference planes. Magnitude of the S-parameters is calculated from the reflected and transmitted power. The power going through a plane is calculated directly from the simulated fields and the relevant S-parameters are determined as follows:

$$S_{11} = \sqrt{\frac{P_{\mathrm{ref}}}{P_{\mathrm{inc}}}} \tag{1}$$

$$S_{21} = \sqrt{\frac{P_{\mathrm{trans}}}{P_{\mathrm{inc}}}} \tag{2}$$

with a generic term (subscripts are omitted)

$$P = \tfrac{1}{2}\mathrm{Re}\left(\oint E \times H^* ds\right) \tag{3}$$

in which P_{inc}, P_{ref}, and P_{trans} denote the incident, reflected, and transmitted powers calculated from the related field components, respectively.

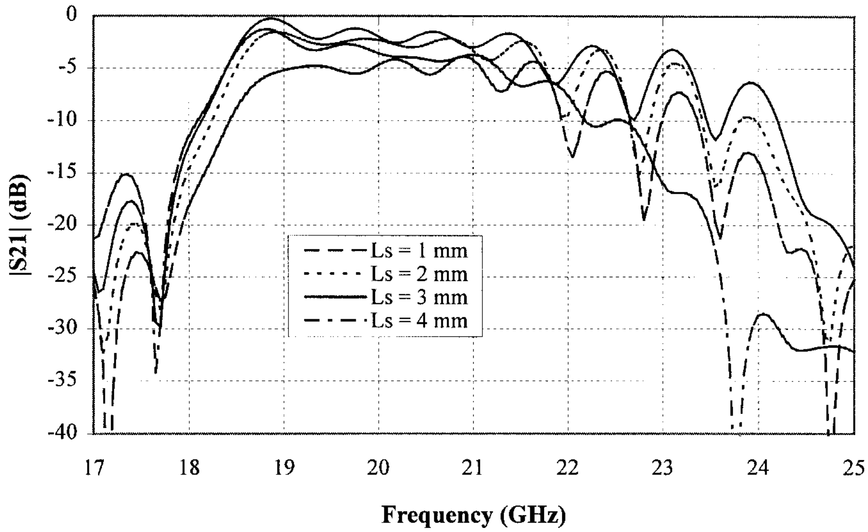

Fig. 3. Bandwidth and transmission performance as a function of the microstrip-line open-end (L_s) with an NRD open-end fixed at $L_w = 2$ mm and the same length slot (l), as shown in Fig. 3.

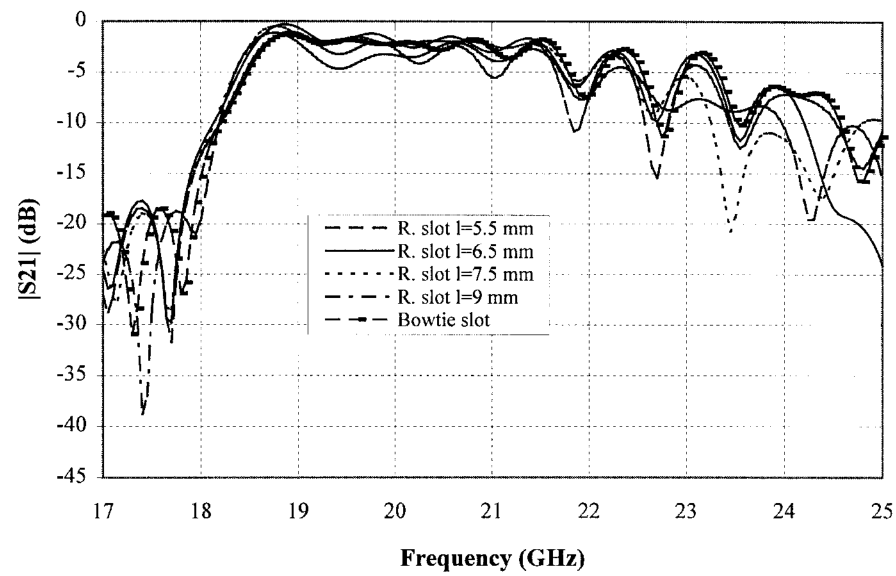

Fig. 4. Bandwidth and transmission performance as a function of the slot length (l) and a bowtie slot with a microstrip-line open-end fixed at $L_w = 3$ mm and an NRD open-end fixed at $L_w = 2$ mm.

III. Theoretical and Experimental Results

With reference to Fig. 1, the NRD-guide is made of a rectangular dielectric strip (Rogers TMM-3, $\epsilon_r = 3.27$) and designed to operate around 20 GHz with $a = 5.08$ mm and $b = 9.814$ mm. Two kinds of dielectric substrates are selected for design of the microstrip line: the RT/Duroid 5880 substrate with $\epsilon_r = 2.3$, thickness $h = 0.508$ mm, and strip width $w = 15.5$ mm, and the TMM-3 substrate with $\epsilon_r = 3.27$, $h = 0.381$ mm, and $w = 0.91$ mm. In this case, the characteristic impedance of the two microstrip lines is 50 Ω. The coupling slot is chosen to have 0.5 mm of width based on our previous experience [5], [6], [8], while the slot length together with other parameters is varied to optimize electrical performance of the transition. The bowtie slot presented in [10] is also studied toward the enhancement of transition coupling characteristics.

The structure to be simulated is enclosed in a rectangular box with a length of 73 mm, width of 60 mm, and height of 16 mm. To obtain accurate results, the spatial increments are chosen to be a function of the smallest wavelength and to take into account fine details of the structure. A fine mesh is used to discretize the region with the highest gradient field and a coarse mesh is used elsewhere. In our case, the smallest mesh value is used to be equal to 0.1905 mm in order to discretize the thickness of the microstrip substrate with two meshes. The slot width is then discretized with three meshes.

Magnitudes of transmission coefficient $|s_{21}|$ obtained by the TLM simulation as a function of frequency for the TMM-3 substrate are plotted in Fig. 2–4. Note that the results involve the two identical transitions which connect the NRD-guide. Generally speaking, the TLM algorithm predicts that both the NRD-guide and microstrip open-ends, as well as the slot length, yield a significant impact on the effective frequency bandwidth and in-band transmission performance. The results shown in Figs. 2 and 3 indicate that the NRD-guide and microstrip open-ends heavily affect the upper end location of the bandwidth, while the cutoff point at the lower end remains unchanged. This can be easily explained by the fact that the cutoff characteristics are essentially determined by the NRD-guide itself

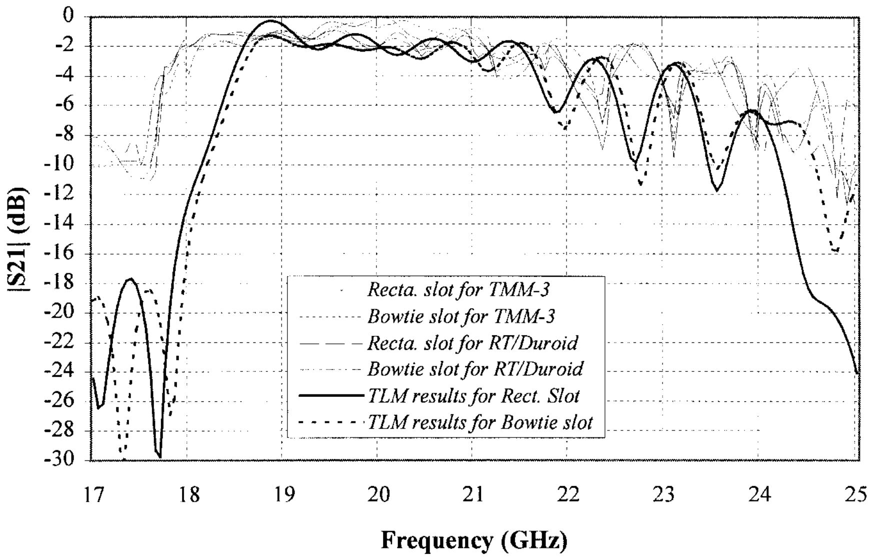

Fig. 5. Experimental and theoretical results presented for transmission performance of the complete back-to-back structure related to TMM-3 ($\epsilon_r = 3.27$) and RT/Duroid 5880 ($\epsilon_r = 2.3$) microstrip-line substrates considering the rectangular slots and bowtie slot.

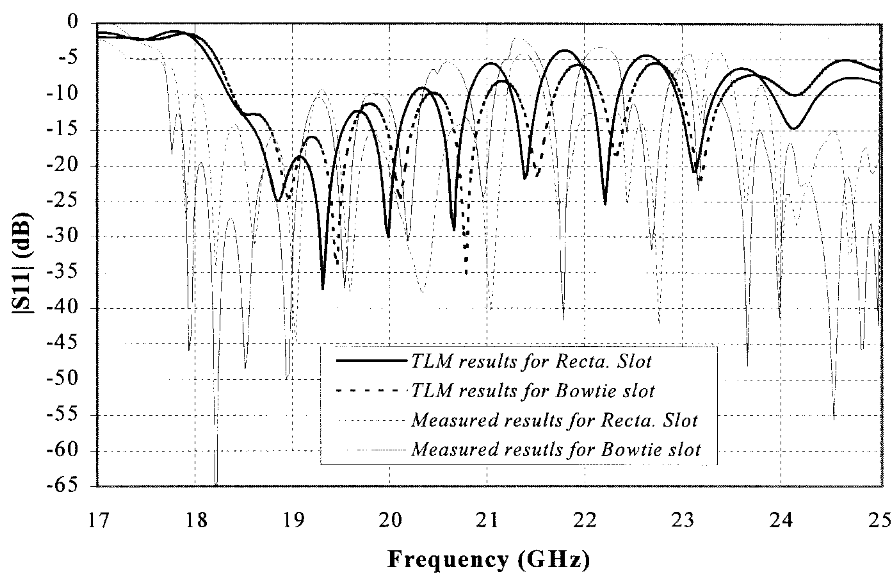

Fig. 6. Experimental and theoretical results of return loss presented for performance assessment of the complete back-to-back structure related to TMM-3 ($\epsilon_r = 3.27$) microstrip-line substrate considering the rectangular slots and bowtie slot.

because the fundamental mode LSM is a dispersive waveguide mode. It is further found that the influence of the NRD-guide open-end on the bandwidth performance is much more important than that of the microstrip-line open-end. It is understandable that the length of both open-ends is frequency sensitive (e.g., quarter-wavelength effect). Since the dispersion is much larger for the NRD-guide than for the microstrip line, the open-end length should be electrically more sensitive for the NRD-guide than for the microstrip line. In addition, the in-band transmission performance (the insertion loss) is also strongly affected by different open-ends (from -0.2 to -5 dB). Therefore, it is necessary to make a design compromise between the bandwidth requirement and in-band performance (concurrent design issue). It also seems that the design of wide-band (or frequency insensitive) open-ends for both dissimilar structures is a solution for a better transition.

Fig. 4 shows the frequency responses of transmission coefficient for different lengths of the rectangular slot, and also for the case of a bowtie slot. It is interesting to see that only the in-band transmission performance is affected while the bandwidth remains the same. This phenomenon suggests that the bandwidth is probably determined by the open-end lengths, while the in-band transmission performance is related to all aspects of the structure. Judging from the point-of-view of the circuit theory, the transmission performance should be determined by the impedance matching, which is actually relevant to the complete structure in this case. Also, the use of the bowtie slot has little improvement or deterioration on the performance compared to its rectangular counterpart, which is quite different from the situation of microstrip line-to-microstrip line presented in [10]. The main reason is that the coupling mechanism is quite different from each other. In our case, the coupling is made through the two dissimilar structures and also two different modes (TEM and LSM modes). In the other case, the coupling is achieved between two identical modes supported by the same type of structures. It can be expected that the impedance of the NRD-guide also differs from that of the microstrip line, while in the other case, the two lines are completely matched in terms of the impedance.

Judging from the results presented here, it is found that an optimum design requires a microstrip-line open-end $L_s = 3$ mm, an NRD-guide open-end $L_w = 2$ mm, and a slot length $l = 6.5$ mm, although this optimization is made with the available results. Note that the ripples in the bandwidth may be caused by a multiple reflection due to mismatch of the NRD-guide with two transitions. With this transition design, the theoretical modeling results show that the complete structure (two identical transitions and lossless microstrip lines, as well as one NRD-guide) is expected to have less than -0.4 dB of insertion loss over the lower end of the bandwidth, while the rest of the bandwidth presents less than -2 dB. With this design, a set of experimental prototypes are fabricated and measured for both rectangular slots and bowtie slot using the two different substrates. Experimental curves for transmission and reflect coefficients are presented and compared to theoretical results in Figs. 5 and 6, respectively, indicating a good agreement with the theoretical prediction, despite the fact that there is a deviation of 500 MHz between them. It also confirms the electrical behavior of the bowtie slot, as discussed above. The difference of bandwidth and the observed deviation between the theoretical and measured results may be attributed to our not-so-good fabrication tolerance since the TMM3 dielectric block is hard to process. The experiment was made simply without mechanical adhesion between the planar circuit and NRD-guide strip, which may cause some unexpected and harmful air gap between them. In the case of using TMM-3 substrate, the transmission is almost constant in the bandwidth of interest and it presents about -1 dB for the complete structure. In the case of the RT/Duroid 5880 substrate, a better transmission takes place around 20 GHz with only -0.2 dB insertion loss, while the rest of the bandwidth is around -1.6 dB. This structure may be used to design, e.g., a narrow-band filter. In all the cases, there is a satisfactory agreement between the TLM and measured results.

IV. Conclusion

The TLM algorithm has been successfully applied to model the transition between an NRD-guide and microstrip line for the newly proposed hybrid-integration technology. The theoretical predictions are found to be in good agreement with the experimental results. It is found that the NRD-guide and microstrip-line open-ends have a significant influence on the bandwidth and in-band transmission performance, while the slot length is only related to the in-band transmission performance. In addition, the NRD-guide open-end is much more sensitive than its microstrip-line counterpart. Different from the case of a microstrip-line-to-microstrip-line coupling scheme, the bowtie slot has little influence on the electrical performance of the transition compared to the rectangular slots. This can be attributed to the two different coupling mechanisms. The designed and measured results are very encouraging for the hybrid-integration scheme.

References

[1] T. Yoneyama and S. Nishida, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1188–1192, Nov. 1981.

[2] ——, *Nonradiative Dielectric Waveguide* (Infrared and Millimeterwaves Series), K. J. Button, Ed. New York: Academic Press, 1984, ch. 2, pp. 61–98.

[3] J. Huang and K. Wu, "A two path multimode bandpass filters using the nonradiative dielectric (NRD) waveguide technology," in *IEEE MTT-S Symp. Dig.*, Orlando, FL, May 14–19, 1995, pp. 1547–1550.

[4] F. Kuroki and T. Yoneyama, "NRD guide digital transceivers for millimeter-wave LAN system," *IEICE Trans. Commun.*, vol. E79-B, pp. 1759–1764, Dec. 1996.

[5] L. Han, K. Wu, and R. Bosisio, "An integrated transition of microstrip to nonradiative dielectric waveguide for microwave and millimeter-wave circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 1091–1096, July 1996.

[6] K. Wu and L. Han, "The hybrid integrated planar/NRD-guide technology: A new concept for low-cost application of microwave and millimeter-wave circuits," in *IEEE MTT-S Int. Microwave Symp.*, San Francisco, CA, June 18–20, 1996, pp. 91–94.

[7] D. Dawn and M. Sachidanada, "Analysis and design of strip line to nonradiative dielectric waveguide," in *Proc. 3rd Asia–Pacific Microwave Conf.*, Tokyo, Japan, 1990, pp. 15–18.

[8] K. Wu and L. Han, "Hybrid integration technology of planar circuits and NRD-guide for cost-effective microwave and millimeter-wave applications," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 946–954, June 1997.

[9] ——, "Integrated planar NRD oscillator suitable for low-cost millimeter-wave applications," *IEEE Microwave Guided-Wave Lett.*, vol. 6, pp. 329–331, Sept. 1996.

[10] C. Chen, M. J. Tsai, and N. G. Alexopoulos, "Optimization of aperture transitions for multiport microstrip circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2457–2465, Dec. 1996.

[11] L. Han, N. Simons, K. Wu, A. Ittipiboon, and M. Cuhaci, "Experimental and numerical analysis of integrated transition of microstrip line-to-NRD-guide," in *Conf. Proc. ANTEM'96*, Montréal, P.Q., Canada, Aug. 6–9, 1996, pp. 15–18.

[12] W. J. R. Hoefer, "The transmission line matrix method—Theory and application," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 882–893, Oct. 1985.

[13] P. B. Johns, "A symmetrical condensed node for the TLM method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 370–377, Apr. 1987.

[14] N. R. S. Simons, A. Sebak, and A. Ittipiboon, "Analysis of aperture coupled microstrip antenna and circuit structures using the transmission line matrix method," *IEEE Antennas Propagat. Mag.*, vol. 37, pp. 27–37, Aug. 1995.