LSE-Mode Balun for Hybrid Integration of NRD-Guide and Microstrip Line

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***Abstract*—A recently proposed hybrid integration technology of NRD-guide and planar circuits provides an alternative for exploiting advantageous features of the two complementary structures in view of three-dimensional circuit design at millimeter-wave frequencies. Such an integration scheme has been developed for use of the second fundamental mode (LSM) having the lowest transmission loss. In this work, a new balun structure (transition) integrating NRD-guide and microstrip line is reported for the first fundamental mode (LSE). A TLM algorithm is used to model and optimize the proposed LSE-mode related NRD-guide/microstrip line transition. Electrical characteristics of the new balun are studied theoretically and experimentally. Calculated and measured results are found to be in good agreement for designed experimental prototypes at 18–22 GHz.**

***Index Terms*—Hybrid integration technology, LSE mode, microstrip line, NRD-guide, TLM method, transition/balun.**

I. Introduction

The ever-increasing demand for low-cost and low-loss millimeter-wave components and systems has stimulated interests searching for new hybrid/monolithic integrated topologies. Currently, there is a trend toward the use of a multilayered three-dimensional (3-D) integration technology involving various planar and nonplanar structures. It has been well known that the nonradiative dielectric (NRD) guide that was proposed in [1] has shown promising electrical and mechanical features for the design of various millimeter-wave components [2]–[4]. Nevertheless, the development of an adequate integration of NRD-guide with planar structure has been a very challenging issue, and this is essentially a critical point for integrating active devices in its building block [5], [6].

To solve such a problem, a new technique based on the concept of an aperture coupling [5], [6] was recently proposed. It makes use of a slot etched on the ground plane of a microstrip line or coplanar waveguide (CPW) vertically coupled to the NRD-guide. This balun (transition) scheme allows to develop a multilayered and multilevel hybrid integration of planar structures and NRD-guides. This new hybrid integration technology may combine advantages of these involved dissimilar geometries while inherent shortcomings of each individual building block can be effectively eliminated [7], [8]. So far, it has been successfully demonstrated through a number of passive and active components, using the LSM mode related baluns. Such an LSM mode, which is actually the second fundamental mode, has the lowest transmission loss [5]–[8]. In this work, a new balun similar to the previous one is reported herewith and proposed for use of the (first) fundamental LSE mode. Brief theoretical analysis and experimental results are presented for K-band applications.

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II. LSE-Mode Balun and Its Design Issues

The fundamental LSE mode, despite its slightly higher ohmic loss as opposed to its LSM counterpart, can of significant interest for design of millimeter-wave circuits. This mode is orthogonal in space with respect to the LSM mode, which can be used in the design of a balanced mixer, for example. In this case, the LSM mode serves as the radio frequency (RF) signal carrier while the LSE mode is responsible for transmission of the LO signal. The orthogonality of the two modes may guarantee the maximum isolation between the RF and LO signals. Other types of application can be found in the design of power divider and combiner [4].

The geometry of a typical LSE-mode balun is shown in Fig. 1. It consists of an (or quasi-) TEM-mode microstrip line deposited on the top of an NRD-guide sharing a common ground plane. The coupling is achieved magnetically through an etched rectangular slot on the ground plane even though other forms of slot can also be considered in the design. The slot orientation defines essentially the operating mode in the NRD-guide. To excite the desired LSE-mode from the microstrip line, the microstrip line should be in the parallel position with respect to the NRD-guide and the coupling slot is oriented in perpendicular to the NRD-guide. In principle, similar rules of designing the LSM-mode balun (or transition) can be directly applied to the case of the proposed LSE-mode.

The modeling and design of such a balun structure are, however, still in an early stage. An approximate model [5] which assumes a series of hypothetical conditions such as very narrow slot topology and well-defined mode profile was used to characterize the LSM-mode baluns. In this 3-D structure, a good balun design to achieve any expected coupling is a rather complex issue because hybrid-mode guided-waves are difficult to characterize. In our work, a TLM algorithm is applied to model the LSE-mode balun, and an orthogonal 3-D adaptive mesh scheme is used to obtain a good space discretization resolution over the structure. An absorbing boundary condition is also applied in reducing our computational window for this unbounded structure. S-parameters are calculated from the reflected and transmitted waves [6].

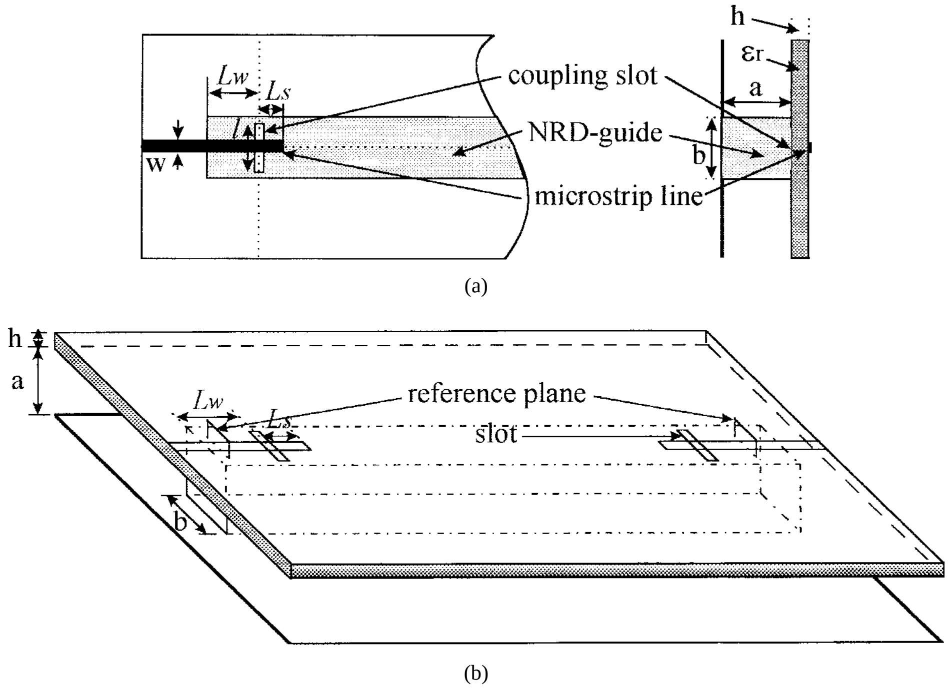

Fig. 1. Three-dimensional view of (a) balun geometry and (b) complete balun/NRD-guide/balun structure designed for simulation and measurement.

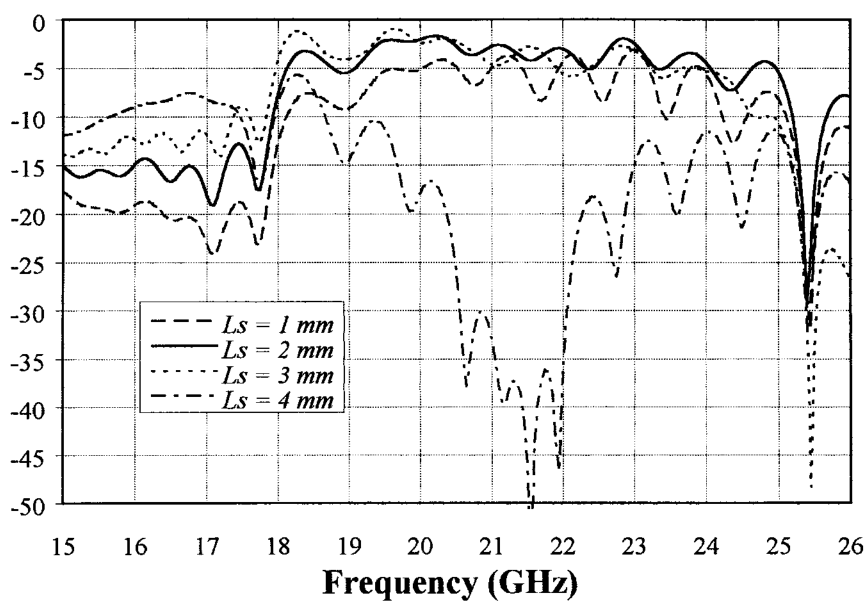

Fig. 2. Bandwidth and transmission characteristics as a function of the microstrip line open-end (L_s) with a NRD open-end fixed at $L_w = 2$ mm and a slot length $l = 6$ mm.

III. Theoretical and Experimental Results

In our examples selected for studying electrical characteristics of K-band LSE-mode balun, the NRD-guide is made of a rectangular dielectric strip with Rogers TMM-3$^{\text{TM}}$, $\varepsilon_r = 3.27$ and it is designed to operate around 20 GHz with $a = 5.08$ mm and $b = 9.814$ mm. To simplify our design procedure, the microstrip line is also fixed at the beginning and it is made of a RT/Duroid 5880 dielectric substrate with $\varepsilon_r = 2.3$ and thickness $h = 0.508$ mm. It is designed to have characteristic impedance of 50 Ω with a strip width of $w = 1.55$ mm. The slot size and other parameters (open-ends of NRD-guide and microstrip line) are kept variable to optimize electrical performance of the LSE-mode balun (wide bandwidth and high coupling efficiency). The structure is simulated in an electrically transparent rectangular box with a size of $93 \times 60 \times 16$ mm^3 (length $\times$ width $\times$ height). To obtain accurate results, the spatial increments are chosen as a function of the smallest wavelength in the TLM algorithm, considering also fine details of the structure. A fine mesh is used to discretize regions with the highest gradient fields and a coarse scheme elsewhere. The smallest mesh value is 0.1905 mm to discretize the thickness of the planar substrate with two meshes.

In the following, our simulated results are presented for a complete experimentally verifiable topology composed of two identical baluns—the input/output microstrip lines with

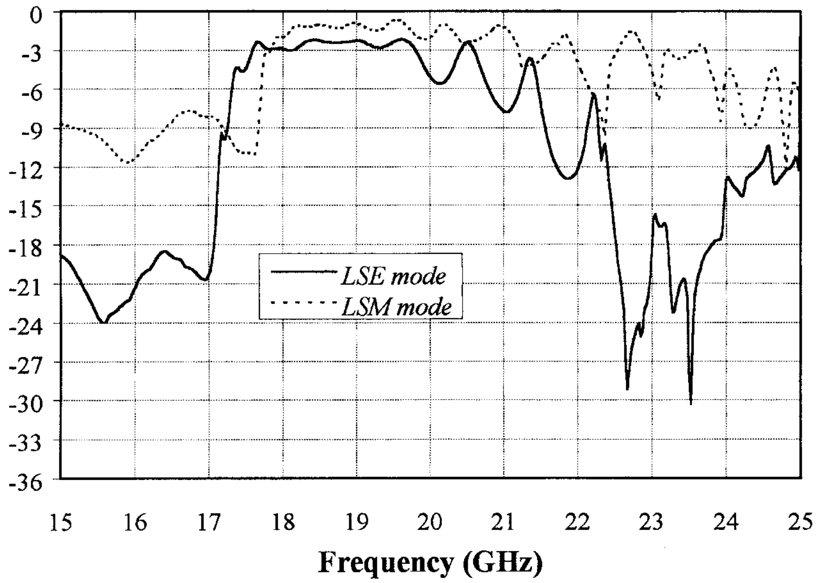

Fig. 3. Experimental results for LSE mode signal transmission of a complete structure as opposed to its LSM mode counterparts.

an identical length as well as a certain length of NRD-guide. Fig. 2 shows a series of simulated transmission coefficients as a function of frequency for different microstrip open-ends. It is interesting to observe that transmission characteristics are significantly affected by the choice of a microstrip open-end even though the operable frequency bandwidth remains relatively stationary. Such characteristics are different from those of LSM balun [6]. Our calculated results (not shown here) indicate that influence of the microstrip open-end and the coupling slot size on the bandwidth performance is much more pronounced than that of the NRD-guide open-end. The curves of Fig. 2 suggest that there is a relatively large design freedom as for the choice of a geometry in achieving an expected transition performance.

With our preliminary analysis, it is found that a good design is identified with a microstrip open-end $L_s = 3$ mm, an NRD-guide open-end $L_w = 4$ mm, and a slot length $l = 6$ mm even though a truly optimum design requires computationally intensive work with the TLM algorithm. Our modeling results show that the complete structure is expected to have less than 2.5 dB of insertion loss around 20 GHz. The observed in-band small ripples may be caused by a multiple reflection due to a mismatch between the two baluns and NRD-guide. Measured results are presented in Fig. 3, showing a good agreement over the useful bandwidth between the modeling and experiments. The observed notches in the measured results at about 22.5 and 23.5 GHz may be attributed to our fabrication tolerance or mechanical assembling problems. With comparison to its LSM-mode counterpart, the LSE-mode balun prototype presents a higher attenuation as expected. The in-band frequency response is rather flat. The slight difference of bandwidth between the predicted and measured results may be attributed to our fabrication tolerance since the TMM3$^{\mathrm{TM}}$ dielectric block is hard to process. In addition, the lower cutoff frequency of the LSE mode as compared with the LSM mode is clearly indicated in the measured results.

IV. Conclusion

A compact balun for LSE-mode circuits and components is proposed for the hybrid integration technology of NRD-guide and planar structure. A TLM algorithm is successfully applied to model this new balun and its modeling results are validated by our measurements. As opposed to the LSM-mode case, it is found that the microstrip open-end and the coupling slot size have a significant influence on the in-band transmission property while the effective bandwidth remains almost stationary. It is found that the LSE-mode transmission presents a higher attenuation than its LSM-mode counterpart. Our designed and fabricated prototype indicates that the in-band frequency response is rather flat, and the proposed LSE-mode balun shows promising applications.

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