Ultrabroad-Band Vertical Transition for Multilayer Integrated Circuits

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***Abstract*— A vertical transition using wide-aperture coupling is proposed for ultrabroad-band design of multilayer integrated circuits. With an electrically wide aperture formed on the common ground plane of two-layered microstrip line structures, a significant enhancement of capacitively series coupling is observed at low frequency. This simple technique realizes a very flat frequency response of transmission over a very broad bandwidth. A two-layered transition is accurately characterized by applying a so-called "short-open calibration" (SOC) scheme to calibrate numerical results obtained from a full-wave method of moments (MoM). The transition shows several attractive features such as ultrabroad bandwidth, low radiation loss, and deep up-band rejection. Predictions are well verified by measurements over a wide frequency range.**

***Index Terms*— Broad-band vertical transition, method of moments (MoM), multilayer circuits.**

I. Introduction

VERTICAL transitions or interconnects using slot-coupled microstrip lines have been extensively studied [1]–[4] and have been instrumental in electromagnetically interconnecting two vertically adjacent planar circuits of different layers in multilayer integrated circuits such as monolithic microwave integrated circuits (MMIC's) and low-temperature cofired-ceramic (LTCC) circuits. Early research was focused on the investigation of transversely oriented slot-coupled lines [1], [2]. To increase useful frequency bandwidth, recent work has been directed to the characterization of vertical transitions with various slot orientations or configurations [3], [4]. These structures operate on the basis of a common mechanism that allows the coupling of two layered lines through the generation of resonant modes in the slot. Such slot-coupled transitions eventually degrade electrical performance of high-density multilayer circuit blocks because of potential radiation and/or interference caused by the slot at resonance.

Stemming from the design concept of a broad-band directional coupler [5], a novel vertical transition with a wide coupling aperture is proposed for bandwidth enhancement and slot-resonance suppression. Its electrical properties are studied by applying a numerical de-embedding technique called short-open calibration (SOC) [6]–[8], to calibrate the calculated parameters obtained from a deterministic full-wave method of moments (MoM) [9]. Predicted results show distinct features of the new structure such as ultrabroad bandwidth, low radiation loss, and deep up-band rejection compared to its conventional counterparts [1]–[4]. Our measured results verify well the theory over a wide frequency range.

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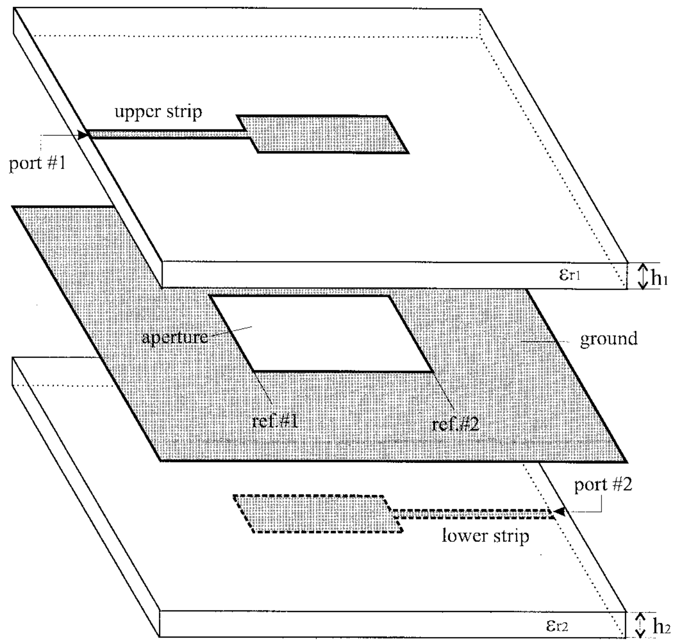

Fig. 1. Layout of the proposed vertical transition of microstrip lines with an electrically wide aperture, which interconnects the upper and lower input/output lines. The transition is embedded in a two-layered structure.

II. Modeling Technique

Fig. 1(a) describes the layout of a two-port vertical transition with a wide aperture formed on the common ground plane of the two-layered structures to provide a fed-through coupling between the upper and lower strips. A deterministic MoM [9] is extended for full-wave modeling of its electrical characteristics in an unbounded space. In this case, electric fields over the aperture can be regarded as a pair of equivalent magnetic current densities having opposite orientation and identical magnitude, which flow on the upper and lower surfaces of the infinitely extended ground plane. As the impressed fields (voltages) backed by a vertical electric plane are simultaneously introduced at each port of two connecting lines far away from the aperture, a source-type algorithm is formulated for an explicit solution of unknown electric/magnetic current densities over the strip/aperture surface. Subsequently, electrical properties of the transition can be characterized by a two-port admittance (Y) matrix, which relates the calculated currents to the impressed voltages.

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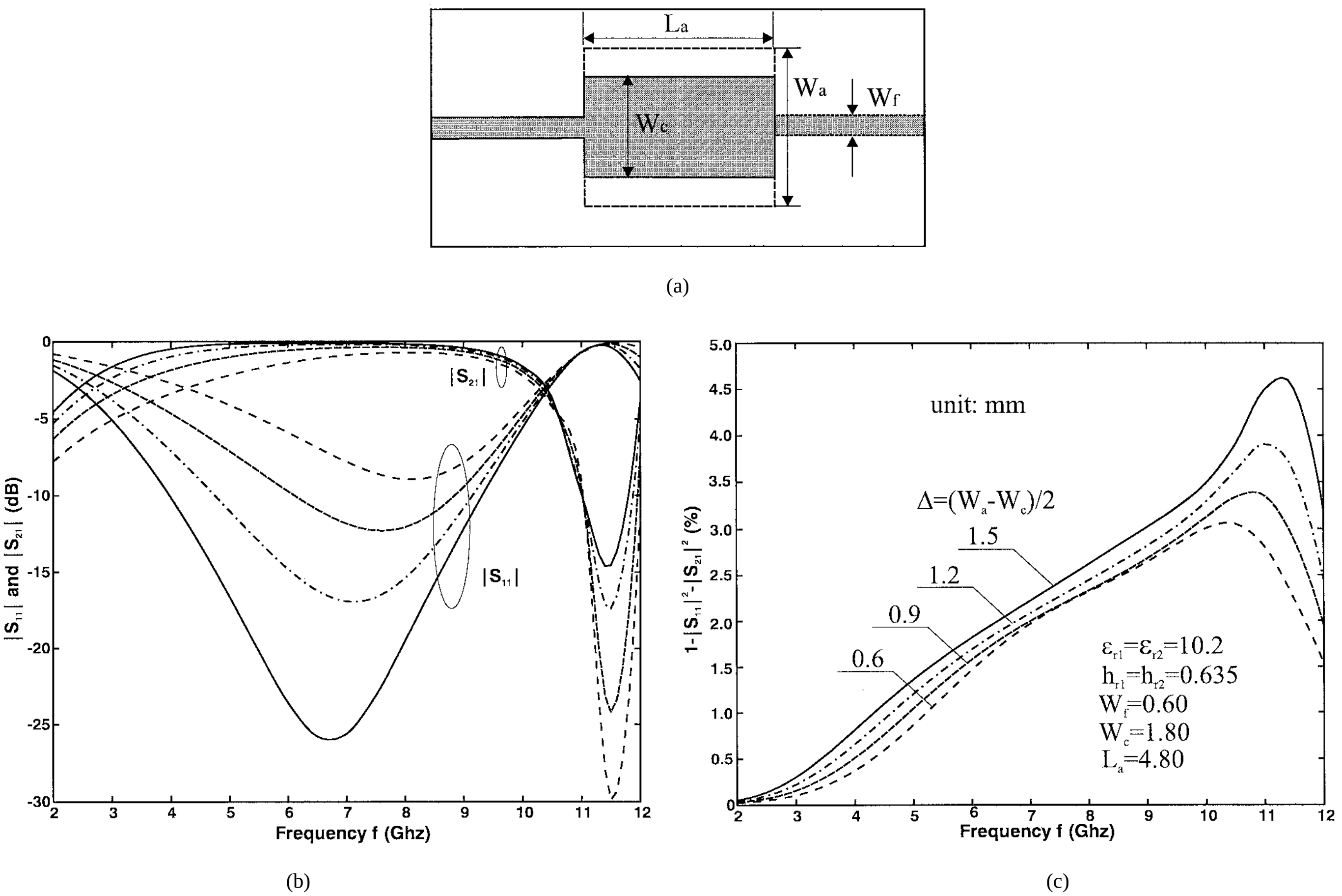

Fig. 2. Top view of the proposed vertical transition and its predicted electrical properties versus various aperture widths. (a) Top view. (b) S-parameters. (c) Radiation loss in percent.

A numerical de-embedding technique called "short-open calibration" [6]–[8] is then applied to de-embed (extract) electrical parameters of the core part of the aperture bounded with two reference planes, namely, *ref.\#1* and *ref.\#2*, as shown in Fig. 1. This procedure is accomplished by evaluating and removing the so-called "error terms" in the source-type MoM algorithm in relation with microstrip discontinuities [6]–[8], with the help of two calibration standards, short and open elements. The error terms involve port discontinuity effects caused by the impressed sources [8] and also inconsistency errors of two-dimensional (2-D) and three-dimensional (3-D) MoM modeling of a uniform line section [6], [7]. Two calibration standards for each line can simply be formulated by modeling a uniform line section, in which one of line terminals is excited by an impressed source while the other is shorted or opened by either perfect electric or magnetic wall. Thus, the Y-matrix can analytically be deduced for the core aperture part at the two ports by removing the two error terms, which are expressed in the form of two ABCD matrices. To visualize transmission properties in an explicit manner, the Y-matrix is further transformed into the S-matrix.

III. Results and Discussion

The following discussion is restricted to the characterization of a two-port symmetrical transition with two identical layers and connecting lines, as depicted in Fig. 2(a). Fig. 2(b) plots predicted S-parameters over a broad range of frequency (2.0–12.0 GHz) against several aperture widths (W_a). As (W_a) is widened from 0.6 to 1.5 mm, useful S_{21} range is extended and improved over low frequency (<5 GHz), which exhibits the enhancement of capacitive coupling between the upper and lower strip surfaces. In this case, the transition can be perceived as an equivalent capacitance that links in series two strips at different layers, similar to the metal–insulator–metal (MIM) capacitor [10]. As frequency increases to around 7.0–8.0 GHz, S_{21} gradually approaches its maximum value (0-dB) in the frequency range while S_{11} drops rapidly. Beyond the point of $f = 8.0$ GHz, useful electrical properties of the transition are gradually degraded. Around $f = 11.5$ GHz, S_{11} goes down to its minimum value for four selected widths, which interestingly forms a deep rejection band. In this case, the effect of an additional series inductance becomes significant since both the coupled strips around the aperture are electrically extended in length. This inductance in parallel with the series capacitance leads to an equivalent *LC* circuit, and thus a *LC* resonance generates the rejection band, as shown in Fig. 2(b). Fig. 2(c) gives the percentage of loss in connection with radiation. As the aperture width (W_a) is enlarged, the radiation loss appears as a slight increase and attains the peak value of about 4.5% at $f = 11.6$ GHz. With reference to the results in Fig. 2(b), the maximum losses are usually happening around the *LC* resonant frequencies.

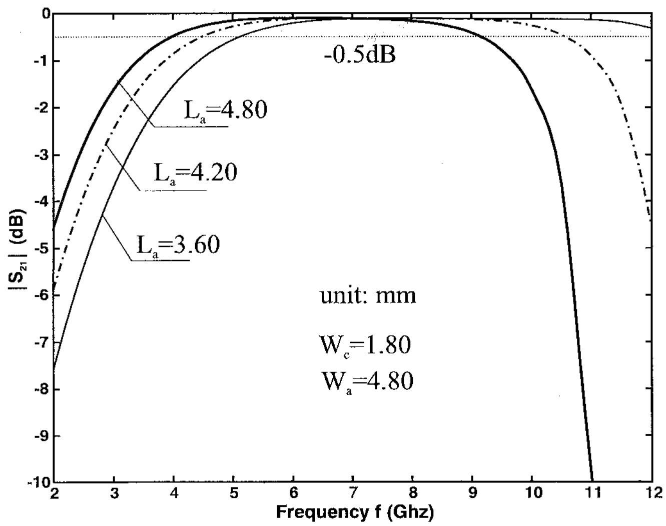

Fig. 3. Predicted insertion loss and frequency response of the bandwidth of a vertical transition versus various aperture lengths.

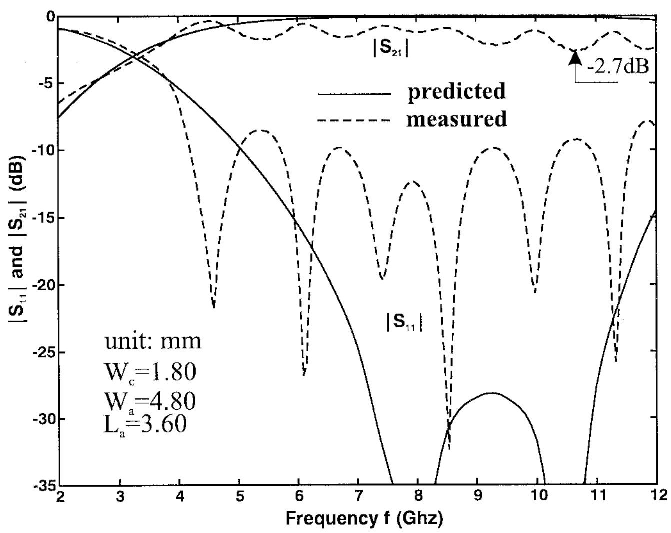

Fig. 4. Predicted and measured S-parameters of a vertical transition.

To further broaden the useful bandwidth of transition, Fig. 3 shows predicted insertion loss S_{21} for a transition with various coupled-strips lengths ($L_a = 3.60, 4.20$, and 4.80 mm). It can be seen from Fig. 3 that the transition always has a very flat and wide bandwidth with S_{21} large than -0.2 dB regardless of the aperture length. In this example, 0.5-dB pass-band is significantly broadened from 52% to 80% as L_a is shortened to 3.60 mm. To confirm the theoretical predictions, a transition with two 50-Ω connecting lines is fabricated by mechanically grouping together two separate substrates. Measured results are plotted in Fig. 4, together with calculated results, which show an ultrabroad-band transmission with S_{21} higher than -2.7 dB over the frequency range (4.0–12.0 GHz). In this experiment, our fabrication and mechanical tolerance problems and measurement errors essentially lead to some discrepancy between the measured and calculated parameters.

IV. Conclusion

In this work, a new vertical transition featuring low insertion loss, ultrabroad bandwidth, low radiation loss, and deep up-band rejection is proposed. This structure is made with an electrically wide aperture formed on the common ground plane of a two-layered structure. Distinct properties of the transition are extracted and exposed by our MoM modeling technique together with a "short-open calibration" (SOC) technique. Preliminary experiments are used to verify the predicted electric performance for the proposed vertical transition over a wide frequency range. As emerging multilayer fabrication technologies are being developed and deployed such as LTCC, this vertical transition may find wide application in the design of broadband high-density multilayer integrated circuits and systems.

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