Millimeter-Wave Monolithic Integrated Circuit Interconnects Using Electromagnetic Field Coupling

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***Abstract*—Standard interconnect and packaging techniques for millimeter-wave monolithic integrated circuits (MIMIC's) tend to get more and more difficult at millimeter-wave frequencies due to the increased influence of discontinuities and tolerances, especially in conjunction with temperature and hermetic sealing. To overcome these problems, a novel concept is proposed based on electromagnetic field coupling. On this basis, coupling structures for feed-throughs out of a package as well as chip interconnects have been designed, fabricated, and tested in a scaled frequency range and in the original millimeter-wave frequency range showing good results with acceptable tolerance requirements.**

I. Introduction

MILLIMETER-wave monolithic integrated circuits (MIMIC's) have been successfully developed during the last few years, and they presently are being introduced into millimeter-wave systems. For civil applications like collision avoidance for cars or communication applications like local area networks (LAN's) or tie lines for mobile communication, low cost is a prime factor. Nevertheless, all circuits and systems have to be protected effectively against environmental loads like water vapor, chemicals, or mechanical stresss. Effective interconnect techniques and hermetic sealing in low-cost packages, therefore, are of major importance.

With increasing frequency, interconnects and packaging of MIMIC's become more and more difficult. Conventional galvanic interconnects from a MIMIC chip to a carrier substrate include strong low-pass type discontinuities due to bond loops (to allow some thermal expansion) and stray capacitances (air gaps due to the tolerances of separating the chips). Compensation of these discontinuities requires tight tolerances and, possibly, techniques for adaptive bonding procedures [1] with additional matching structures on the MIMIC's. Flip-chip mounting shows problems with heat sinks on the one hand, and on the other hand, interferences of the electromagnetic field of the chip with the carrier substrate may degrade circuit performance [2].

At millimeter-wave frequencies, the wall thickness of a package compared to wavelength can no longer be neglected. This leads, once again, to strong discontinuities for feed-through elements. Furthermore, with respect to hermetic sealing, every galvanic feed-through is a potential source of leakage.

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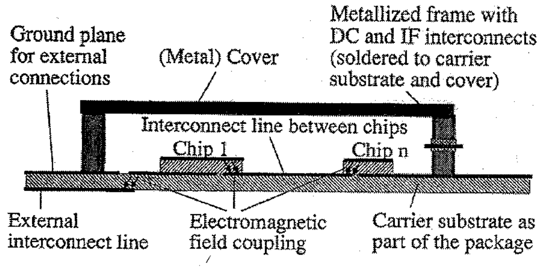

Fig. 1. Basic principle of the proposed interconnect/packaging solution for MIMIC's.

On the other hand, wavelengths at millimeter-wave frequencies, especially in conjunction with GaAs or alumina substrates, are rather small. Therefore, electromagnetic coupling between (typically $\lambda/4$) transmission line segments with absolute lengths of a fraction of a millimeter become compatible with the size of MIMIC's [3]–[5]. Based on this principle, a novel concept for interconnects and packaging is proposed (Fig. 1). The MIMIC chips are placed on a common carrier substrate which, at the same time, acts as an integral part of a package. The millimeter-wave signals are coupled electromagnetically, i.e., without galvanic connection, from the chips to the carrier, while direct current (dc) and intermediate frequency (IF) signals are connected by conventionally bonding across the edge of the chip. A millimeter-wave interconnect from the interior of the package to the outside, once again, can be achieved by electromagnetic coupling through the carrier substrate. A seal ring containing feed-through elements for dc and IF can be soldered flash onto the carrier substrate.

At a frequency of 80 GHz, the length of a typical structure for electromagnetic coupling of MIMIC's is about 300 μm. On the chip itself, only a 50-Ω transmission line section is necessary, while, in some cases, a small matching structure is placed on the carrier substrate.

Using field coupling instead of conventional galvanic interconnects, the bond process as a complicated and highly accurate process step at millimeter-frequencies can be omitted. Furthermore, it will be shown that the tolerance requirements for electromagnetic coupling are not very critical.

In Figs. 2 and 3, a number of basic structures for electromagnetic coupling are shown. In Fig. 2, transitions from coplanar line to microstrip, from microstrip to waveguide, and from microstrip to microstrip are presented which can

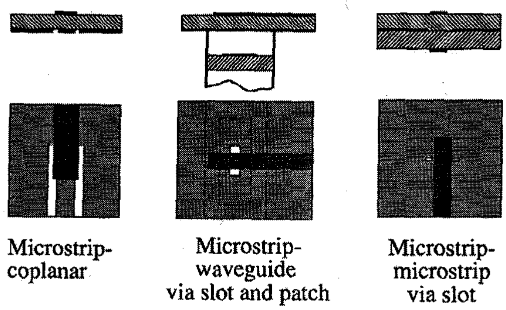

Fig. 2. Principles of electromagnetic coupling through a carrier substrate.

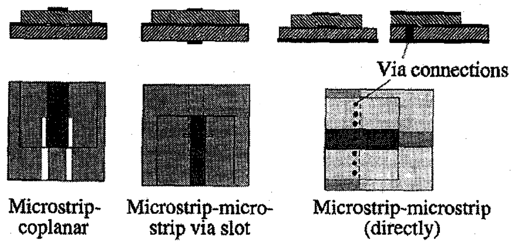

Fig. 3. Some possible configurations for interconnects from a millimeter-wave MIMIC chip to a carrier substrate.

be employed as package feed-throughs. Similar configurations are available for chip interconnects (Fig. 3).

The coupling structures including some matching elements on the carrier substrate have been analyzed and designed by a combination of full-wave methods and standard CAD procedures. Part of these structures have been designed and tested in a scaled version, so that they could easily be realized without GaAs technology using soft substrates. To this end, RT-Duroid 6010 was used, having a permittivity ($\epsilon_r = 11$) similar to GaAs or alumina. In the original frequency range, a transition from microstrip to waveguide has been realized at 80 GHz, and a transition from a microstrip line on GaAs to a coplanar line on an alumina carrier substrate was designed and tested at 35 GHz.

II. Numerical Methods

In this section, only a rather general description of the major numerical method, the mode matching technique, is given. A detailed description of the methods would by far go beyond the scope of the this paper. For details, therefore, the reader is referred to the specific literature.

The mode matching technique [6], [7] is a very general tool in the numerical computation of electromagnetic field problems. For calculating the scattering parameters of a (three-dimensional) transition, the structure of interest is enclosed by a perfectly conducting shielding and divided (longitudinally) into pieces of generalized waveguides of constant cross section, see Fig 4. For these particular cross sections, complete sets of expansion functions (modes) are determined. To this end, field set-ups are made in partially homogeneous sections, and the continuity conditions at the respective interfaces are fulfilled in a first step of the mode matching procedure. The resulting modes include propagating as well as evanescent and

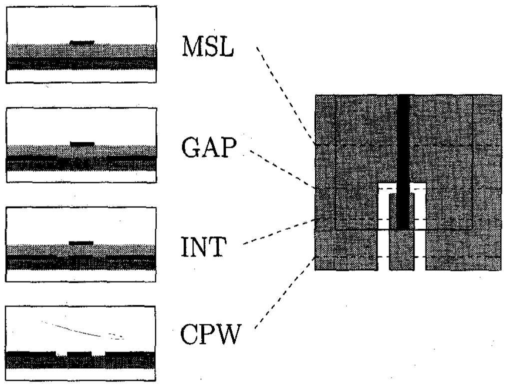

Fig. 4. Decomposition of a three-dimensional transition into different piecewise homogeneous cross sections. The following denotations are made: MSL: microstrip line; GAP: cross section of open ended coplanar line; INT: coupling area; CPW: coplanar line.

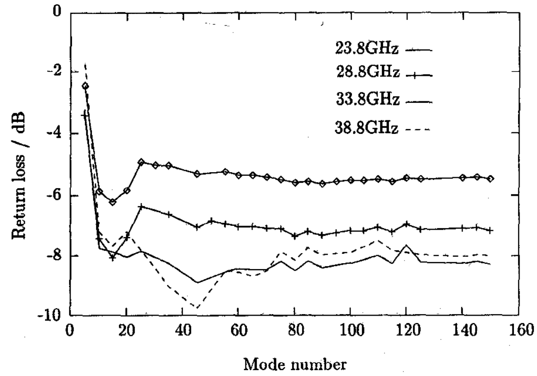

Fig. 5. Convergence behavior of the structure of Fig. 4 for different frequencies in dependence of the number of modes used in every cross section. (The mode spectrum includes complex modes.)

complex modes [8], [9], representing—in the case of an infinite number of modes—a complete set of functions for the fields in these generalized waveguides.

Mode matching is applied again to fulfill the continuity conditions at the interfaces between the different waveguide sections. While theoretically, an infinite number of modes have to be considered, the resulting system of equations has to be solved for a finite number of modes. This number of modes is chosen to give a sufficient convergence of the results, as shown in Fig. 5, where the behavior of the return loss of a typical structure is plotted as a function of the number of modes taken into account in each cross section.

As a second method, the spectral domain technique [10]–[13] was chosen. This method is less general, but it proves more effective in the case of laterally homogeneous dielectric layers with rather thin metallization, and is used here for the computation of the microstrip to waveguide [14] and the microstrip-to-microstrip transition via a slot.

Although the basic coupling structures—with a length of about a quarter wavelength—were designed for maximum coupling, the resulting return loss was not entirely sufficient for the desired applications. Therefore, matching elements were added on the carrier substrate. To this end, the coupling

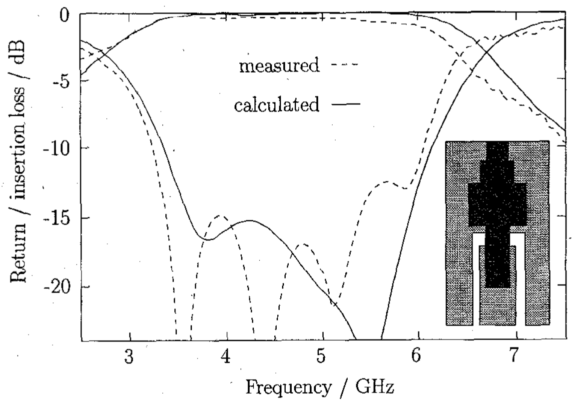

Fig. 6. Transition from microstrip to coplanar line used as feed-through with matching structure. $\epsilon_r = 11$, overlapping length $d = 4.4$ mm, gap $g = 1.0$ mm, $w_{msl} = 2.4$ mm, $w_{cpw} = 2.8$ mm, $s_{cpw} = 0.8$ mm, and $h = 1.27$ mm.

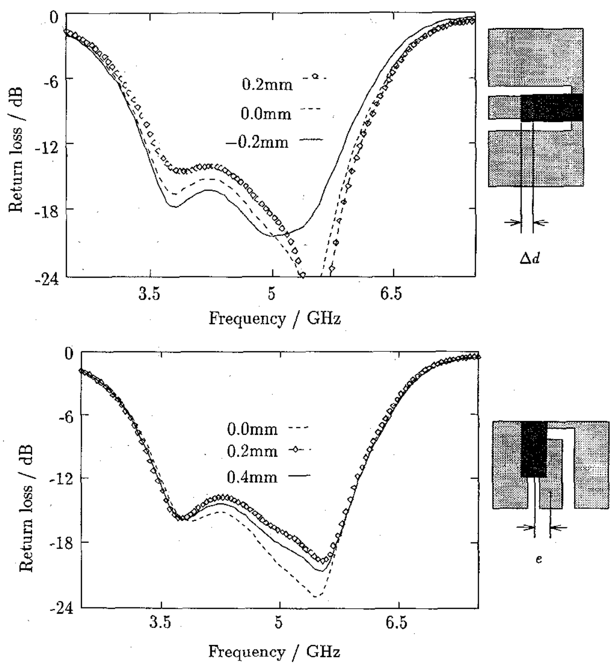

Fig. 7. Tolerance analysis of longitudinal Δd and lateral displacement e of microstrip line versus coplanar line.

elements were represented by equivalent circuits, and these elements were used as integral parts for a standard bandpass filter design. The additional filter reactances were then realized as transmission line elements.

III. Results

A. Feed-Through Transitions

As a first example, a transition from coplanar waveguide to microstrip line on the opposite side of a carrier substrate was investigated in detail in a scaled frequency range. To improve the basic transition as shown in Fig. 2 (left side), a simple, small matching network was added on the microstrip side, giving 50% bandwidth at 15 dB return loss, see Fig. 6. Taking into account some reflections from the transitions to the coaxial measurement system, very close agreement between theory and experiment can be found.

To check possible tolerances with respect to the adjustment of top and bottom metallization, the influence of a lateral and longitudinal shift between the two planes has also been investigated. In Fig. 7, the calculated dependencies of longitudinal and lateral displacements are shown. Only a small shift of the center frequency and a small degradation of the return loss can be stated.

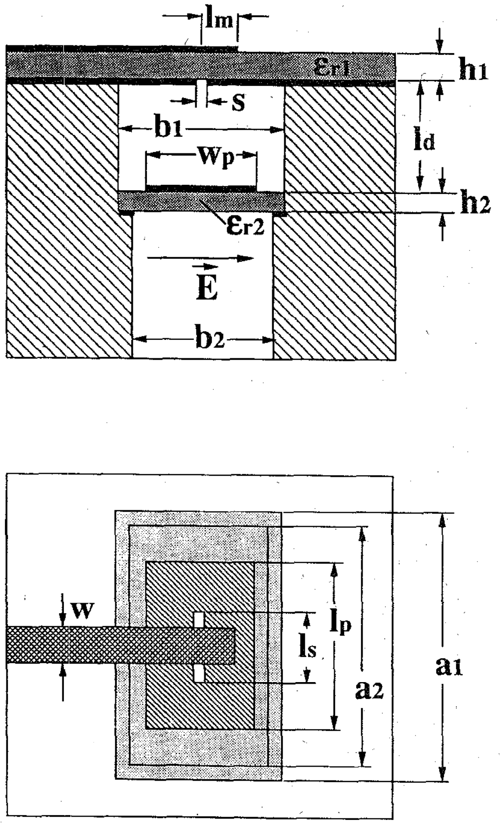

Fig. 8. Microstrip-to-metal waveguide transition.

Although planar lines are of major interest for low-cost millimeter-wave systems, interconnects to metal waveguide are required in several cases for antennas, high-Q oscillators or filters. To this end, a novel transition from the microstrip to metal waveguide compatible with planar integrated circuits was proposed and investigated in [14], see Fig. 2. For applications at millimeter-wave frequencies, the basic structure was modified according to Fig. 8. From the microstrip line, the power is fed via a slot to an additional substrate with a patch radiating into the waveguide. This substrate is placed on a small step in the waveguide width. In this way, it is positioned automatically, and by adding a small rim of metallization to its bottom edges, it can be soldered to the waveguide step sealing the waveguide hermetically. Fig. 9 shows return and insertion loss of two of these transitions placed back to back, connected by a 21.8-mm long microstrip line on a 0.15-mm thick alumina substrate. With an attenuation of the microstrip line of 0.08 dB/mm, an insertion loss of 0.4 dB per transition results.

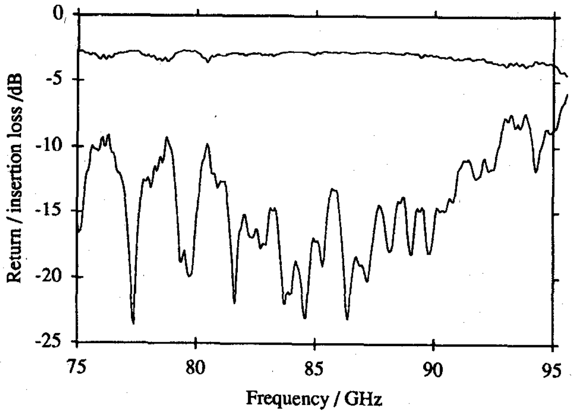

Fig. 9. Experimental results of two modified waveguide-to-microstrip transitions for 85 GHz. $a_1 = 3.7$ mm, $b_1 = 2.15$ mm, $a_2 = 3.1$ mm, $b_2 = 1.55$ mm, $s = 0.2$ mm, $l_s = 0.64$ mm, $l_d = 0.16$ mm, $l_m = 0.12$ mm, $w_p = 1.04$ mm, $l_p = 0.61$ mm, $w = 0.154$ mm, $h_1 = 0.15$ mm, $h_2 = 0.11$ mm, $\epsilon_{r2} = 3.75$, and the microstrip line length is 21.8 mm (between centers of slots).

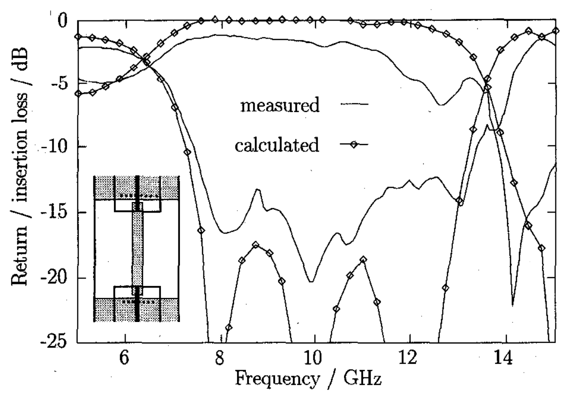

Fig. 10. Theoretical and measured scattering parameters of a scaled chip interconnect, using the direct transition from microstrip to microstrip. $\epsilon_{\text{chip}} = 11$, $h_{\text{chip}} = 0.635$ mm, $w_{\text{chip}} = 0.54$ mm, $\epsilon_{car.} = 11$, $h_{car.} = 1.27$ mm, $w_{car.} = 1.21$ mm, $x = 0.8$ mm, $g = 0.4$ mm, and $d = 2.8$ mm.

B. Chip Interconnects

For an electromagnetic coupling from a MIMIC chip to a carrier substrate, a direct transition from a microstrip line on a chip to a microstrip line on a carrier substrate [Fig. 3 (left)] and a transition from a microstrip line on the MIMIC to a coplanar waveguide on a carrier substrate [Fig. 3 (right)] have been investigated.

For the direct transition from microstrip to microstrip line, some vias in the carrier substrate are necessary, connecting the two different ground planes. In the mode matching analysis of the transition, the vias are simulated by an electric wall. The return loss is better than 15 dB over 40% bandwidth without any additional matching structures. To facilitate processing and measurements, a frequency scaled model on a soft substrate was investigated. Good agreement between theoretical and experimental data for two transitions placed back to back can be seen, see Fig. 10. With increasing frequency, losses increase due to the connecting microstrip lines and due to some leakage of surface waves into the relatively thick carrier substrate used.

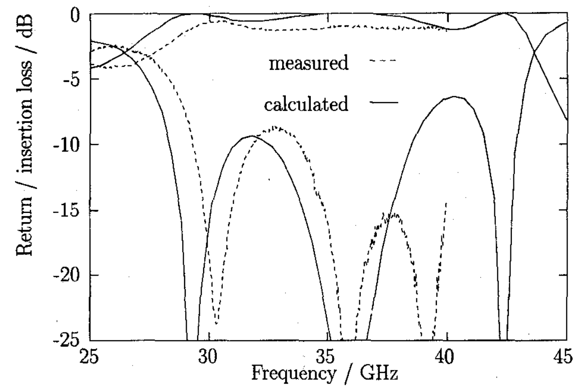

Fig. 11. Theoretical and experimental scattering parameters of two back-to-back transitions from coplanar line to microstrip with matching network. $\epsilon_{\text{chip}} = 12.95$, $h_{\text{chip}} = 150$ μm, $w_{\text{chip}} = 145$ μm, $\epsilon_{car.} = 9.9$, $h_{car.} = 381$ μm, $w_{car.} = 500$ μm, $s_{car.} = 150$ μm, $g = 120$ μm, $d = 740$ μm, $\epsilon_{\text{glue}} = 3.5$, and $h_{\text{glue}} = 5$ μm.

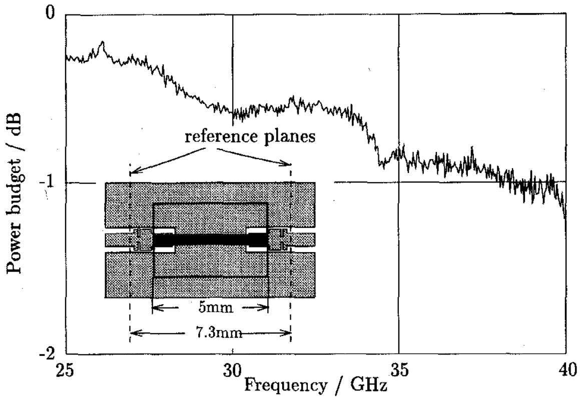

Fig. 12. Experimental power budget $(|S_{11}|^2 + |S_{21}|^2)^{1/2}$, for the complete structure between the designated reference planes.

The transition from microstrip to coplanar line, however, proved to be the simplest and most effective coupling structure. For a realistic simulation, a transition from a microstrip line on a 0.15-mm thick GaAs substrate to a coplanar line on an alumina carrier substrate was designed. As mentioned above, a small matching circuit was placed on the carrier substrate. For the experimental setup, a GaAs substrate with a homogeneous microstrip line, but without ground metallization, was glued on the carrier substrate, thus resulting in two transitions back to back. As normal epoxy glue material has a low dielectric constant, it exhibits a non-negligible influence on the transition performance, and the thin epoxy layer (here assumed to be 5 μm) has to be included in the design.

Figure 11 shows the theoretical and experimental transmission properties of the double transition. A bandwidth of nearly 15 GHz can be stated, sufficient for most millimeter-wave applications. The results show an excellent agreement between measurement and theory. To evaluate the losses, a power budget based on the experimental scattering parameters was made (Fig. 12), showing an overall loss in the range of 0.5 to 1.3 dB.

IV. Conclusion

A novel concept for interconnect techniques and package feed-through structures for MIMIC's has been presented based on electromagnetic coupling. Scaled, as well as original structures, have been designed and tested, showing the feasibility of this concept. The realization of interconnects to a 35 GHz MIMIC amplifier is going on just now.

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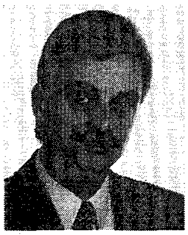

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