Interconnect and Packaging Techniques for Complex Millimeter Wave Front-Ends

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1. Introduction

Modern mm-wave sensors, e.g. for traffic applications, or communication front-ends for local area networks (LANs), tie lines to mobile communication base stations, or mobile mm-wave communication systems (micro cell communication) require high performance but low cost production [1], [2]. To this end, a combination of planar transmission line circuits (coplanar or microstrip lines) with metal waveguide for low loss filters and diplexers is used in many cases (Fig. 1). Furthermore,

- standard designs for planar hybrid or monolithic integrated circuits (MMICs) should be used, or even standard components from a large scale production should be employed.
- effective and accurate methods (full-wave designs) for the critical circuit elements are necessary. If possible, tuning of components should be avoided or at least kept to a minimum.
- good interconnects between the different parts of the front-end have to be ensured.
- the assembly of the components should be as easy as possible.
- the front-end has to be shielded against environmental influences (water, vapor, chemicals, etc.) by a suitable package.
- the front-end with the package has to withstand a defined temperature range.
- the different materials of front-end and package should match with respect to thermal expansion.
- heat generated in a circuit has to be effectively transferred to the outside.

Although mm-waves exhibit a number of advantages like small size, low weight, wide bandwidth, or reduced interaction with other services, tolerance requirements due to the shorter wavelengths, increased reflections at discontinuities and interconnects, and possible package resonances require precautions during design, fabrication and assembling [3] - [10].

2. Communication front-end as example

A number of techniques for packaging and interconnects will be described in this paper with the example of a typical communication front-end. Its basic block diagram is given in Fig. 1. The front-end consists both of planar circuits and metal waveguide components. The general setup of the different parts of the system is shown in Fig. 2.

The planar circuits are based on a multilayer LTCC substrate [11] containing waveguide-to-microstrip transitions, a number of hybrid MICs and the interconnect elements for MMICs. The carrier substrate is placed on top of a carrier structure fabricated by metal injection molding (MIM) based on steel powder. This already provides a reasonable heat sink; should this not be sufficient, an insert of copper-molybdenium can be soldered into a special grove in this carrier. A metallized plastic cover protects the circuit. This cover includes part of the waveguide-to-microstrip transitions (backshort) and a channel structure forming waveguides below cut-off and separating the different parts of the planar circuits.

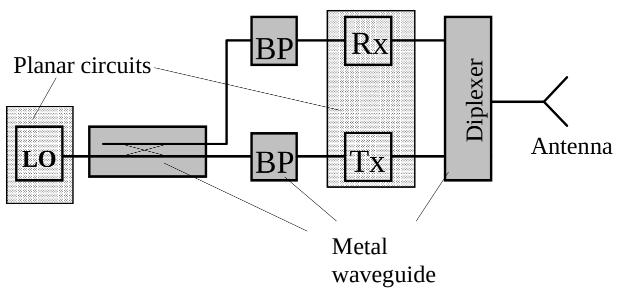

Fig. 1: Principle setup of a typical communication module (BP: bandpass filter, Tx: transmitter, Rx: receiver, LO: local oscillator**).**

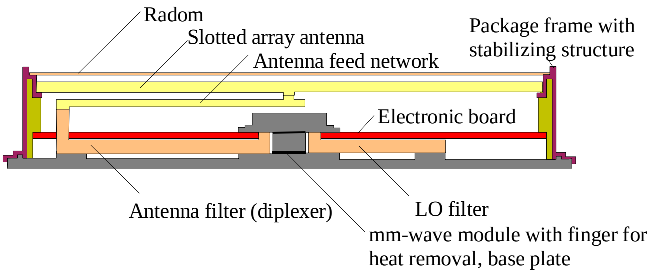

Fig. 2: Basic mechanical setup of the communication system.

The waveguide filters, the diplexer [12] and a 3 dB coupler are fabricated using plastic injection molding and electroplating. The antenna consists of a waveguide slotted array structure etched from a metal sheet and fed by a ridged waveguide feed network – once again fabricated using plastic injection molding.

3. Feed-through structures

The microwave interconnects between the different parts of the planar circuits (interconnects between the different package channels) can be realized via a lower metallization level of the carrier substrate. A direct feed-through structure uses vias from a microstrip line to a triplate line and back; should a DC separation be necessary, or if the top layer of the carrier substrate must not be perforated (possible loss of hermeticity), a slot coupling between microstrip and triplate line is possible, too (Fig. 3).

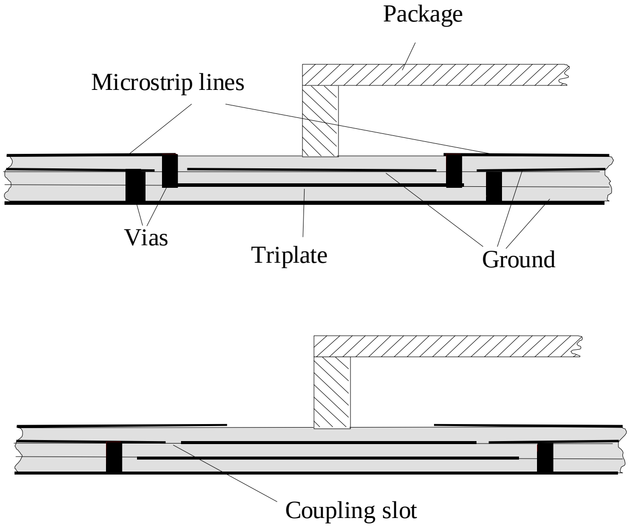

Fig. 3: Cross section of two possible feed-through structures using multilayer substrates.

Such an electromagnetically coupled feed-through structure has been designed for the 28 GHz range [13]; theoretical mm-wave results are given in Fig. 4. To test the transition independently of the LTCC technology process using more simple means, a frequency scaled version on Duroid substrate (ε_r = 10.8) was designed, fabricated and tested. Fig. 5 displays theoretical and experimental results of this scaled transition; the basic performance is met quite well, although some problems occurred bonding the different substrate layers together without air gap, resulting in some deviation between experimental and calculated results.
As transition to the waveguide circuits, modified transitions according to [14] or [15] may be employed.
For lower frequency signals (IF, DC), a number of coaxial feed-through elements are integrated into the MIM carrier structure.

4. Interconnects to MMICs

The most easy way of adding MMICs to the planar circuitry would be just placing them on top of the LTCC substrate (Fig. 6). Using microstrip lines on the carrier substrate, vias have to connect the different ground planes of MMIC and carrier substrate. The bonding between the microstrip lines on the MMIC and the LTCC substrate can be done by bond ribbons. Theoretical calculations (FDTD) and measured results of a single transition of this type (deembedded from the results of two transitions back-to-back with different interconnect line lengths) are given in Fig. 7. Furthermore, the interconnect to a MMIC amplifier was tested (Fig. 8). The experimental performance of the MMIC amplifier connected in that way is plotted in Fig. 9 and compared to a standard on-wafer measurement. Up to about 30 ... 40 GHz, this type of transition is reasonably good; problems occur, however, at higher frequencies.

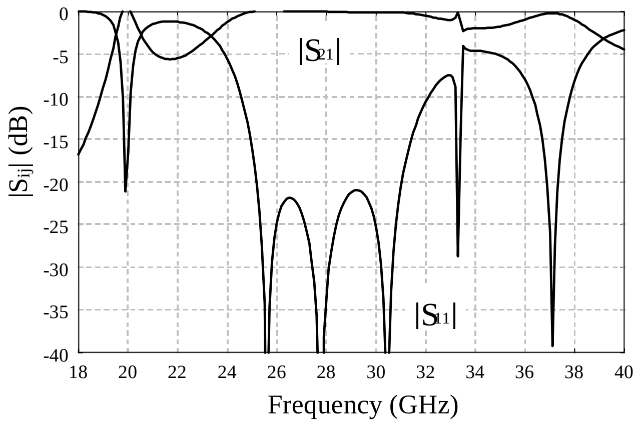

Fig. 4: Transmission behavior of an electromagnetically coupled feed-through structure using a multilayer substrate.

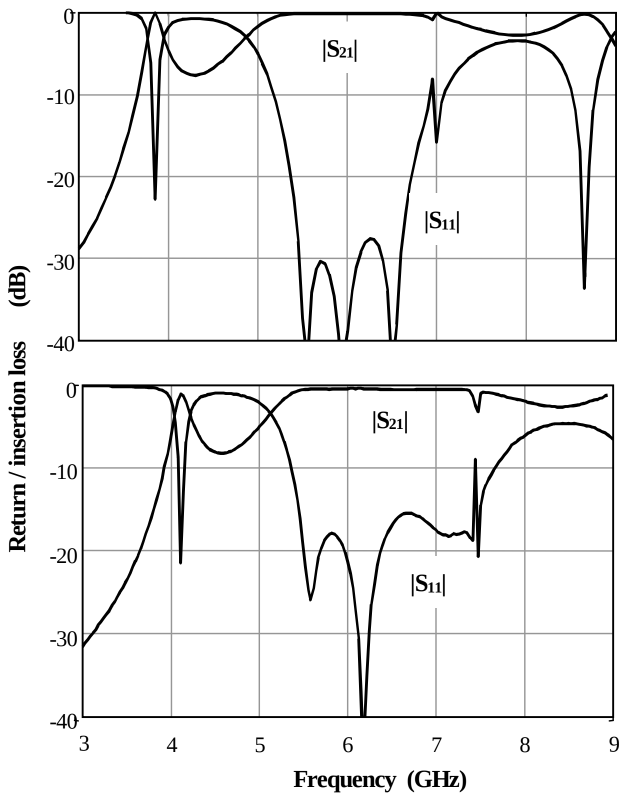

Fig. 5: Theoretical (top) and experimental (bottom) results of a frequency scaled feed-through structure according to Fig. 3 (bottom).

Instead of the microstrip lines on the carrier substrate, coplanar lines with their ground plane in the same level as the MMIC ground plane can be used equally [16] and [9].

Results of a single ribbon bonded transition from a microstrip line to a coplanar line on a carrier substrate are shown in Fig. 10, the performance of a MMIC connected in the same way (Fig. 11) is given in Fig. 12.

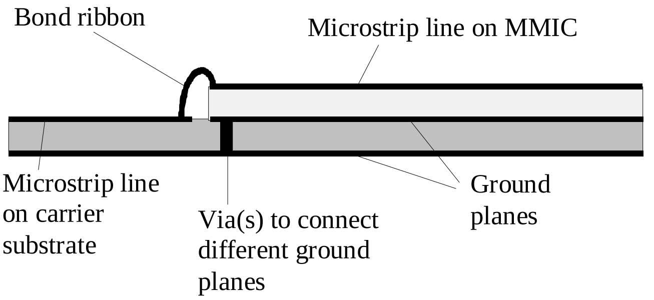

Fig. 6: Cross section of microstrip – microstrip bond interconnect.

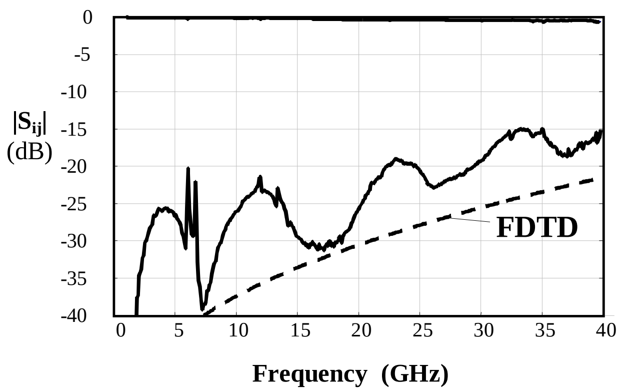

Fig 7: Measured insertion and return loss of a single microstrip-microstrip bond interconnect.

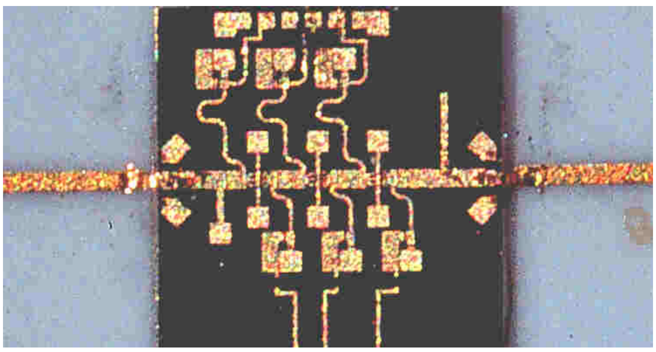

Fig. 8: Photograph of a MMIC amplifier mounted on top of a microstrip carrier substrate and conneted by bond ribbons.

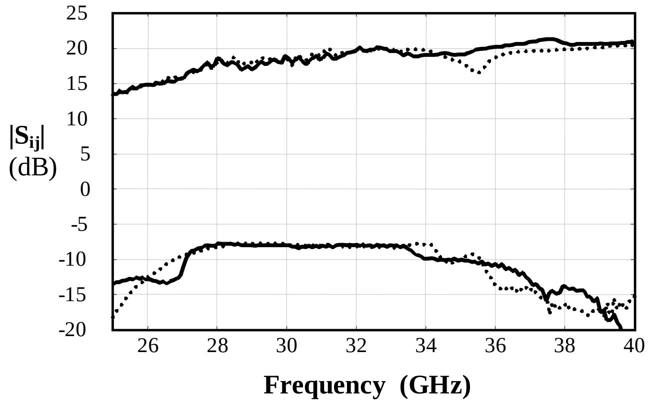

Fig. 9: Measured insertion and return loss of a MMIC amplifier (GaAs substrate height 0.15 mm). Dotted lines: direct on-wafer measurement. Solid lines: bonded according to Fig. 6.

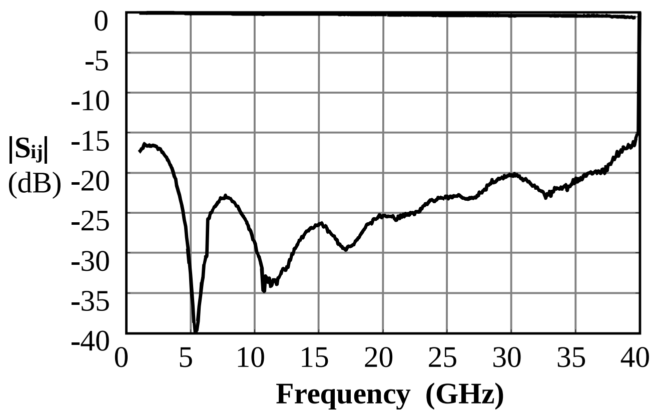

Fig. 10: Measured insertion and return loss of a single transition from microstrip line on top of a coplanar line on a carrier substrate (alumina substrates, substrate height 0.127 mm).

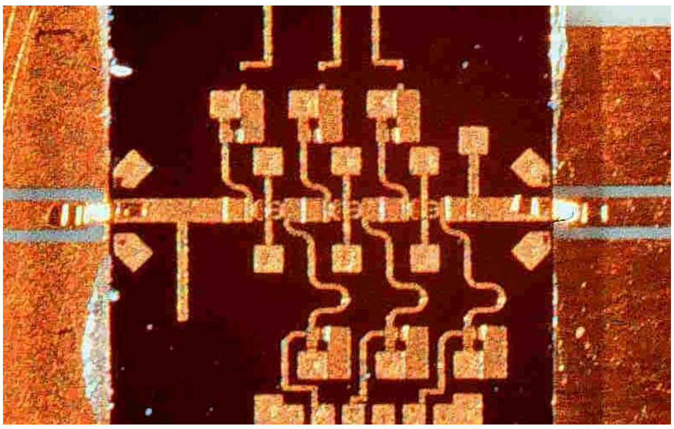

Fig. 11: Photograph of a MMIC amplifier mounted on top of a coplanar carrier substrate and connected by a bond ribbon.

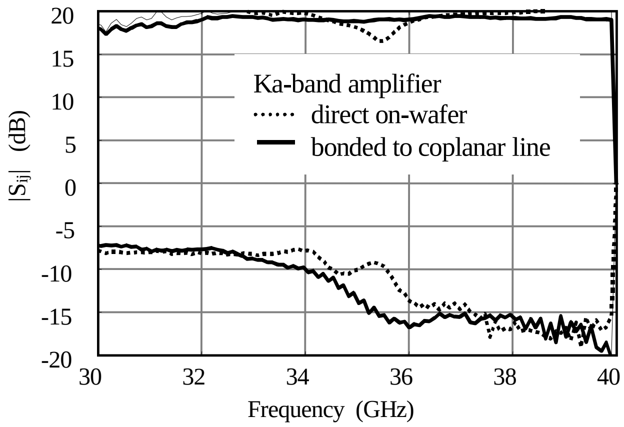

Fig. 12: Measured insertion and return loss of a MMIC amplifier placed on top of a coplanar carrier substrate (GaAs substrate height 0.15 mm). Dotted lines: direct on-wafer measurement. Solid lines: bonded to the coplanar line with a ribbon.

As an alternative to bonded interconnects, electromagnetic field coupling has been demonstrated in [17]. This type of interconnect has been improved in the meantime by the possibility of integrated means for on-wafer measurement without via holes which would disturb the interconnect performance [18]. To this end, quarter-wave stub structures – rather small at mm-waves - are placed besides the microstrip line on a MMIC (Fig. 13, left side).

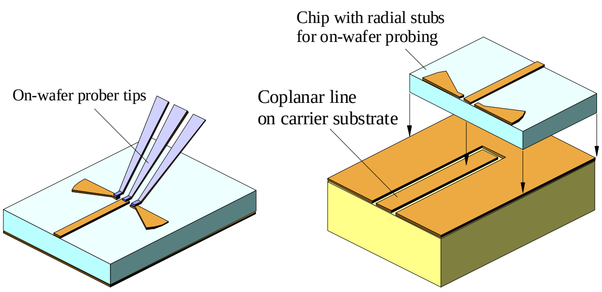

Fig. 13: Arrangements for electromagnetic field coupling of MMICs including on-wafer measurements without via holes.

After on-wafer tests, the chips can be separated and mounted using field coupling as shown in Fig. 13, right side [19]. A frequency scaled test structure was fabricated at 20 GHz. The transition from the on-wafer probe to the microstrip line is plotted in Fig. 14, showing an excellent performance. In Fig. 15, results of an electromagnetically coupled transition of the same microstrip line to a coplanar carrier substrate are shown. Some tolerances of the employed alumina substrates led to a slight modification of the experimental results.

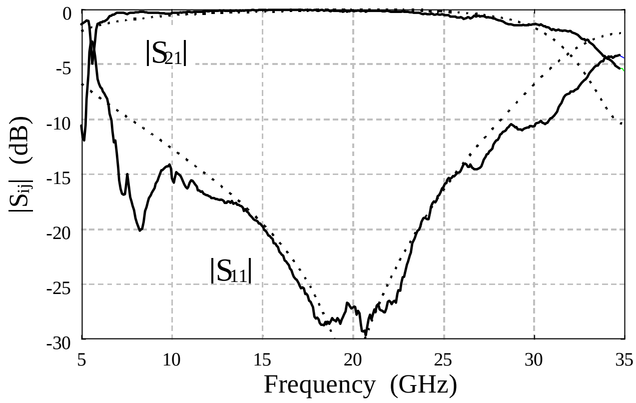

Fig. 14: Theoretical (dotted lines) and experimental (solid lines) results of the transition from the on-wafer probe to a microstrip line without via holes.

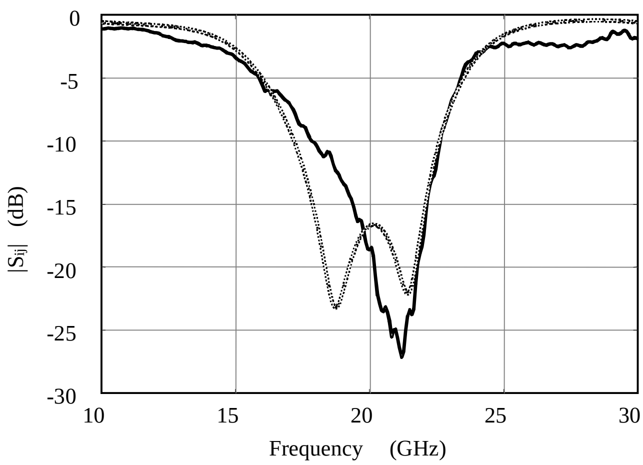

Fig. 15: Theoretical (dotted lines) and experimental (solid lines) results of an electromagnetically coupled transition from microstrip line to coplanar line on a carrier substrate.

5. Waveguide components

For the front-end according to Figs. 1 and 2, two standard waveguide filters combined with a 3 dB coupler were designed for the LO (Fig. 16), and a modified arrangement was chosen for the diplexer (Fig. 17). By replacing inductive irises with short-circuited T-junctions as inverter circuits, stop band poles in the frequency response are created and can be placed at either side of the filter pass-band [12]. For a given out-of-band attenuation - especially if this is required close to the filter pass-band, this allows the number of physical resonators to be reduced and, therefore, leads to lower insertion loss compared to standard filter designs.
Fig. 18 gives design and measured results of such a diplexer, fabricated, in a first step, from aluminum, showing an insertion loss of ca. 0.6 dB and a rejection of better than 60 dB in the respective other passband.

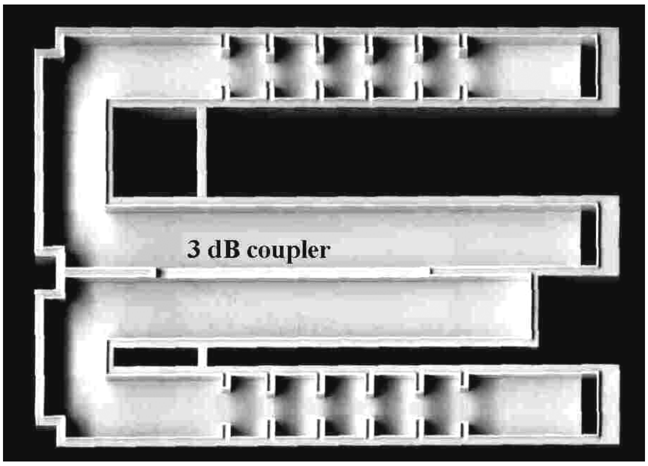

Fig. 16: Photograph of a filter block including two 5 resonator chebishev filters and a 3 dB coupler. The block is fabricated using plastic injection molding.

The two filter blocks as shown in Figs. 16 and 17 are already fabricated as plastic parts. After electroplating, a fully metallized printed circuit board is soldered to the top of the filters.

For a low-cost, high volume fabrication using plastic injection molding, some modifications already have to be considered during the design. To avoid, as far as possible, tensions within the material, wall thickness has to be constant, i.e. iris thickness and the thickness of walls between waveguide sections (see Figs. 16 and 17) have to be set to a common value – 1.2 mm in this case.

Further problems with respect to tolerances of the production process have to be taken into account. The shrinking of the injection molded plastic parts during cooling, on the one hand, can be precalculated to some extent; this however, is not accurate enough for the fabrication of the filters. The parts fabricated from one form, however, are nearly identical one to the other. Therefore, in the design of the filters, cylindrical posts as tuning elements were included in the resonators. In the injection form, this corresponds to holes at the respective positions; the depths of the hole are adjusted by screws. First samples of the filters then are fabricated with the post height being zero. External screws are used to trim the filter response, and the resulting post heights are adjusted in the form. Once the filters produced with this modified form have an acceptable performance, the reproducibility during production is assumed to be good enough. Fig. 19 gives results of the (externally tuned) LO filter arrangement compared to the design performance. It should be noted that these results include the coupling loss of the 3 dB coupler; therefore the filter insertion loss is less than 0.6 dB, and both return loss and transmission behavior are close to the design.

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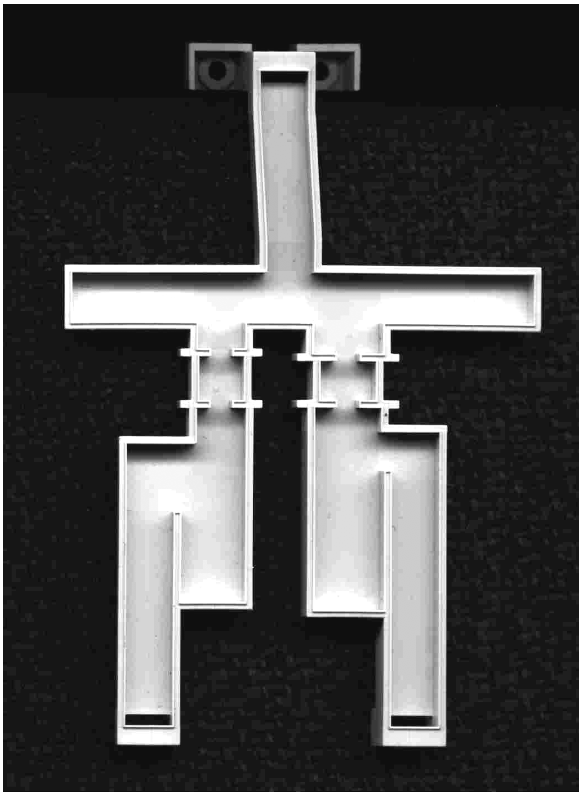

Fig. 17: Photograph of a diplexer. The block is fabricated using plastic injection molding.

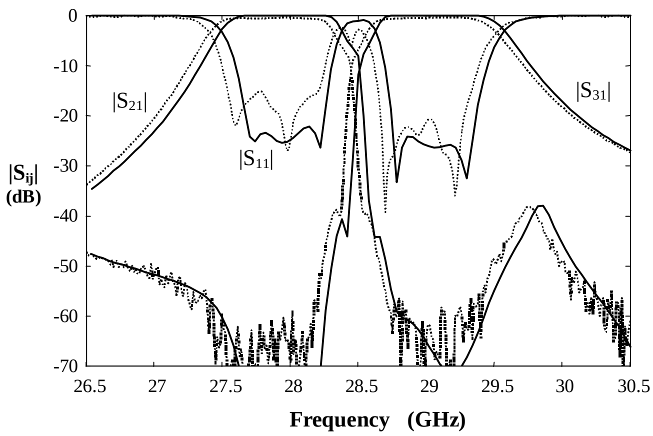

Fig. 18: Theoretical and experimental results of the 28 GHz diplexer machined from aluminum.

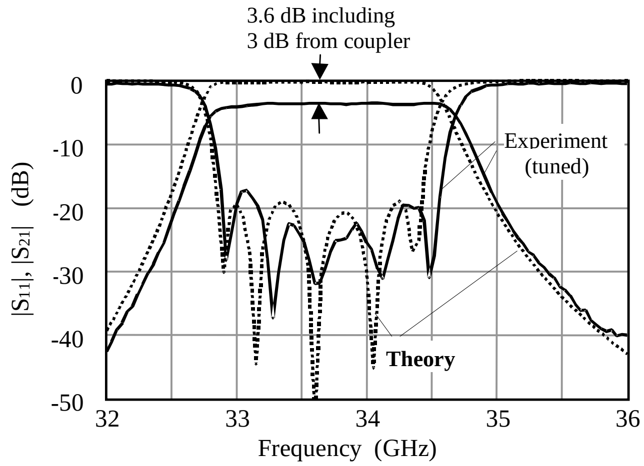

Fig. 19: Return and insertion loss of the LO filter block after tuning, compared to the design characteristics of a single filter.

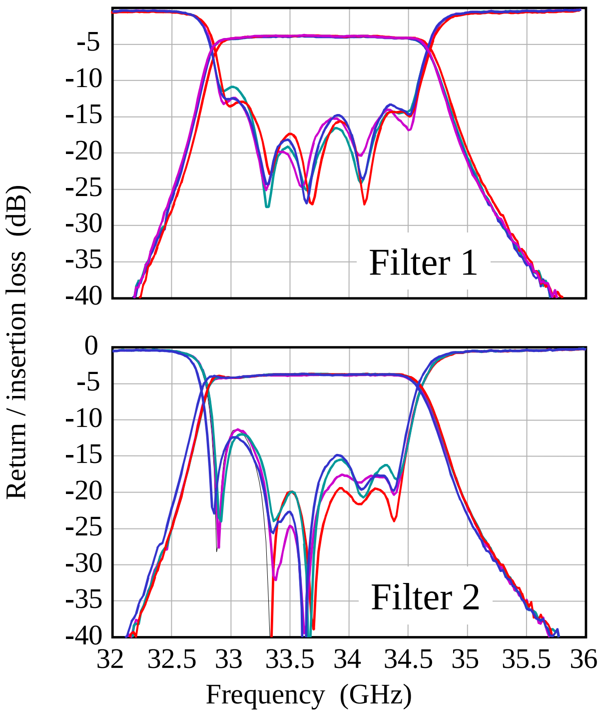

Fig. 20: Experimental results of eight different filters (4 blocks) fabricated by plastic injection molding including the matching structures.

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