Innovative Packaging and Fabrication Concept for a 28 GHz Communication Front-End

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SUMMARY Millimeter-wave systems increasingly are entering into commercial systems, both for communication and sensors for traffic or industrial applications. In many cases, circuit technology of the involved front-ends includes monolithic and hybrid integrated circuits and even waveguide components like filters or antenna feeds. In addition to the standard technical and environmental requirements, these front-ends have to be fabricated in large quantities at very low cost.
After a short review of the problems and some general interconnect and packaging techniques for mm-wave front-ends, achievements of a research program will be presented at the example of components for a 28 GHz communication front-end. Emphasis is put on a novel feed-through structure using multilayer carrier substrates for mm-wave circuits, some advances in electromagnetic field coupling for interconnects to mm-wave MMICs, and the realization of packages including waveguide components by plastic injection molding and electroplating. Results of filters and a diplexer produced in this way are shown, including pretuning of the filters to compensate the shrinking of the plastic parts during cooling.
key words: *packaging, interconnects, fabrication techniques, plastic injection molding, waveguide filters*

1. Introduction

In recent years, great efforts have been undertaken to develop mm-wave monolithic integrated circuits (MIMICs) which now are being introduced into radar [1], [2] and communication equipment [3].
Typical examples are mm-wave sensors for automotive 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). For such low-cost civil systems, however, there is still a lack of reliable techniques for production, packaging, and assembly of the mm-wave front-ends, including MIMICs, hybrid integrated circuits, and partly even metal waveguide.
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 [4] - [10].

This contribution will describe research and development efforts to enable a cost-effective front-end design and fabrication techniques for mm-wave communication equipment at the example of a 28 GHz transceiver unit [11], [12], together with some more general considerations. Some specific packaging and interconnect aspects as well as some novel fabrication techniques will be described in detail.

Already during the system and RF design of a mm-wave front-end, a number of items should be considered:

- The system designers should be aware of special mm-wave aspects differing from lower frequency rules. A typical source of problems arises from the choice of absolute channel spacings as these are used at 5 GHz, for example. At 30 GHz, a channel spacing of 100 MHz is equivalent to a relative frequency fraction of 0.3% only. No mm-wave filter is able to separate this spacing at reasonable losses and fabrication cost (tolerances!) .
- Types of circuits and transmission lines (e.g. microstrip, coplanar line, waveguide) should be selected in such a way that best overall system properties and cost can be achieved. Not only the chip area of a MMIC is important, but also the effective integration of all elements into the front-end and a good overall performance.
- Standard designs for planar hybrid or monolithic integrated circuits (MMICs) should be used as far as possible, 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.
- Heat generated in a circuit has to be effectively

transferred to the outside.

- The front-end with the package has to withstand the required temperature range.
- The different materials of front-end and package should match with respect to thermal expansion.

2. General description of the 28 GHz front-end

The 28 GHz front-end as demonstrated in this paper includes a combination of planar transmission line circuits (coplanar or microstrip lines) with metal waveguide for low loss filters and diplexers (Fig. 1). The basic mechanical setup of the different parts of the system is shown in Fig. 2. The planar circuits are integrated on a multilayer low temperature cofired ceramic (LTCC) substrate [13] containing waveguide-to-microstrip transitions, a number of hybrid MICs and the interconnect elements for MMICs. The LTCC substrate is placed on top of a carrier element fabricated by metal injection molding (MIM) based on steel powder, followed by electroplating. This technique results in an easy to fabricate structure which already provides a high mechanical and temperature stability and a reasonable heat sink; should this not be sufficient, an insert of copper-molybdenium can be soldered into a special grove in this carrier. Reduced height waveguide channels as part of waveguide-to-microstrip transitions [14], [15] and holes for glass beads (DC and IF interconnects) are already integrated into this part. A metallized plastic cover fixed on top of the carrier structure protects the circuits. This cover is fabricated by plastic injection molding again, and it includes further parts of the waveguide-to-microstrip transitions (backshorts) and a channel structure forming waveguides below cut-off and separating the different sections of the planar circuits. The waveguide filters, the diplexer [16] and a 3 dB coupler are fabricated using plastic injection molding and electroplating.

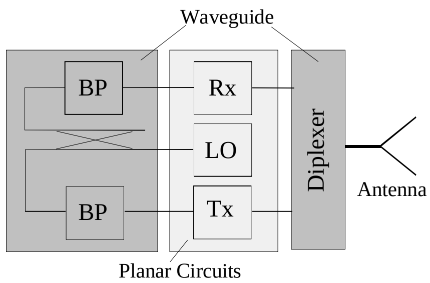

Fig. 1: Basic block diagram of a typical communication module (BP: band pass filter, Tx: transmitter, Rx: receiver, LO: local oscillator).

A photograph of the carrier structure, its cover, and the waveguide filter sections is given in Fig. 3. The antenna will consist 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.

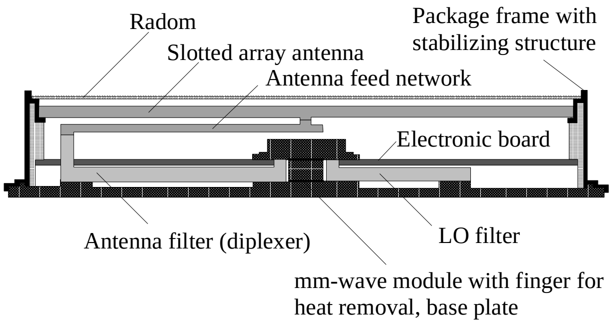

Fig. 2: Basic mechanical setup of the communication system.

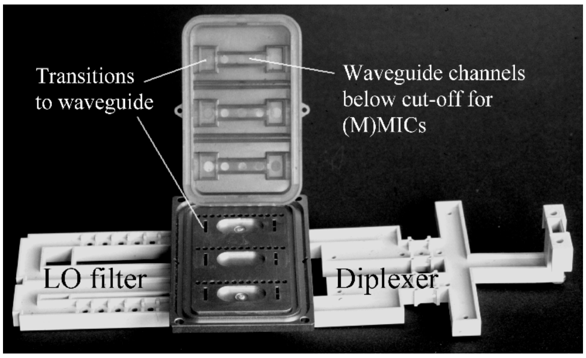

Fig. 3: Photograph of front-end parts using injection molding techniques. (The size of the structure may be derived from a comparison with the waveguide width of 7.12 mm).

3. Millimeter-wave feed-through elements

RF 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 multilayer LTCC carrier substrate (Fig. 4). A direct feed-through structure uses vias from a microstrip line to a triplate line and back to microstrip. 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.4, bottom). To prevent power leakage into the parallel plate waveguide formed by the two ground planes, vias have to be arranged around the transitions between microstrip and triplate both for via interconnects and field coupling.

An electromagnetically coupled feed-through structure of this type has been designed for the 28 GHz range [17]; theoretical results calculated with finite differences in the time domain method (FDTD) are given in Fig. 5. Special attention had to be paid to resonances due to the cavity formed by the vias. The resonances are rather sharp, so that specific care has to be taken to model them correctly with FDTD in a reasonable computation time. This finally could be done employing a system identification method together with the FDTD [18]. Finally, the resonances could be shifted out of the band of operation modifying the via positions.

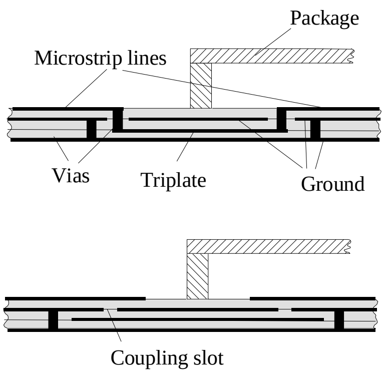

Fig. 4: Cross sections of two possible feed-through structures using multilayer substrates.

To test the transition independently of the LTCC technology process using more simple means, a frequency scaled model on Duroid substrate (h = 0.635 mm, dielectric constant 10.8) was designed, fabricated and tested. Fig. 6 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.

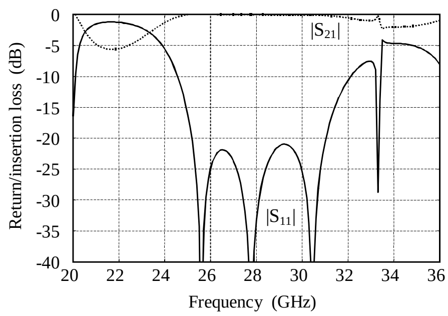

Fig. 5: Theoretical transmission behavior of a 28 GHz electromagnetically coupled feed-through structure using a multilayer substrate.

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. 7). 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. 8. Up to about 25 ... 30 GHz, this type of transition is reasonably good; problems occur, however, at frequencies above 40 GHz.

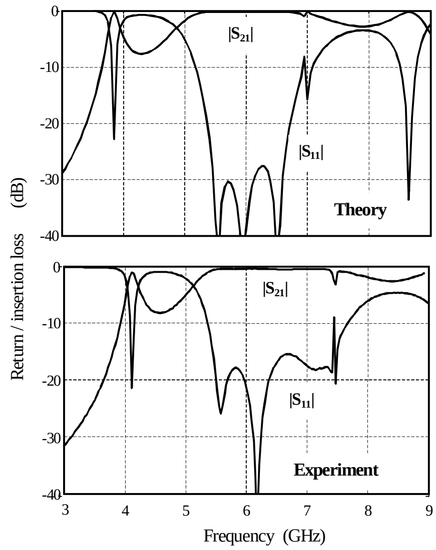

Fig. 6: Theoretical (top) and experimental (bottom) results of a frequency scaled electromagnetically coupled feed-through structure according to Fig. 4.

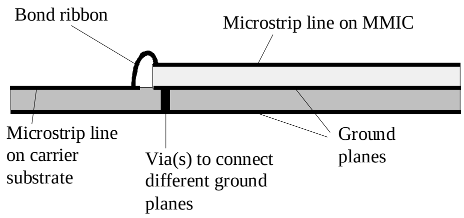

Fig. 7: Cross section of a bond interconnect from a microstrip type MMIC placed on top of a carrier substrate with a microstrip interconnect line.

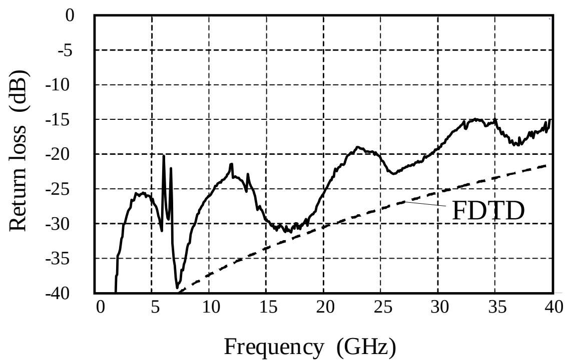

Fig 8: Computed and measured return loss of a single microstrip-microstrip bond interconnect according to Fig. 7.

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 [9] and [19]; this avoids the extra via inductances and the related process steps. Results of a single ribbon bonded transition from a microstrip line to a coplanar line on a carrier substrate are shown in Fig. 9. In this case, a return loss of better than –20 dB is demonstrated up to 35 GHz.

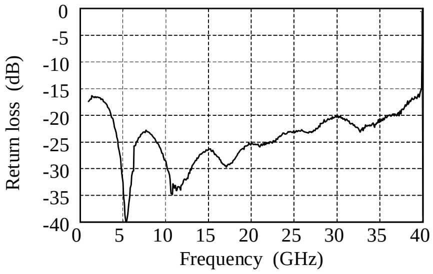

Fig. 9: Measured return loss of a single transition from a microstrip type MMIC placed on top of a carrier substrate with a coplanar interconnect line (alumina substrates, substrate height 0.127 mm).

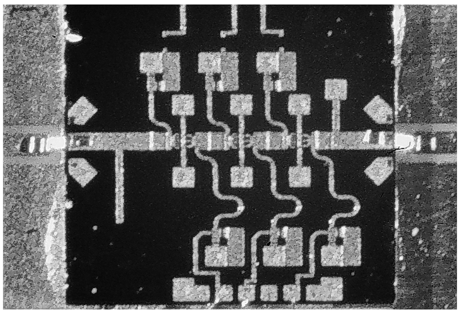

Fig. 10: Photograph of a MMIC amplifier mounted on top of a coplanar carrier substrate and connected by bond ribbons.

The performance of a MMIC connected in this way (Fig. 10) is given in Fig. 11. A very similar performance of the amplifier with both direct on-wafer measurements and testing via the bond interconnects (on-wafer measurement on the carrier substrate) can be stated. During the direct on-wafer measurements, some problems occurred with the calibration, resulting in some dip around 35 GHz.

As an alternative to bonded interconnects, electromagnetic field coupling has been demonstrated in [20]. 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), [21]. To this end, quarter-wave stub structures – rather small at mm-waves - are placed besides the microstrip line on a MMIC (Fig. 12, left side). After on-wafer tests, the chips can be separated and mounted using field coupling as shown in Fig. 12, right side [22]. At 20 GHz, a frequency scaled test structure was designed based on FDTD calculations and fabricated. The transition from the on-wafer probe to the microstrip line is plotted in Fig. 13, showing an excellent performance. In Fig. 14, results of an electromagnetically coupled transition of the same microstrip line to a coplanar carrier substrate are shown. On the carrier substrate, some small matching network was added for best performance. This does not, however, take any area on the MMIC. Some problem with the air gap between the employed alumina substrates led to a slight deterioration of the experimental results compared to the theoretical performance.

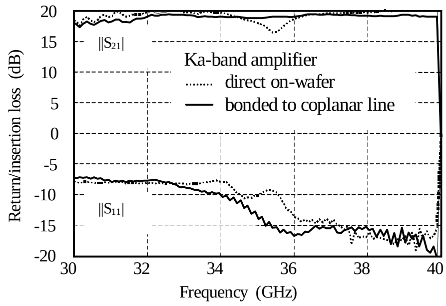

Fig. 11: Measured return and insertion loss of a MMIC amplifier placed on top of a coplanar carrier substrate (GaAs substrate height 0.15 mm).
Dotted lines: direct on-wafer measurement on the MMIC.
Solid lines: MMIC bonded to the coplanar line with bond ribbons, measured on-wafer on the carrier substrate.

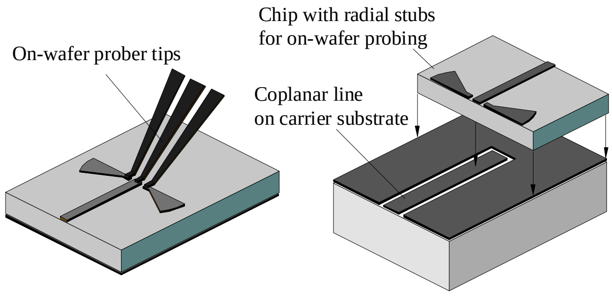

Fig. 12: Arrangements for electromagnetic field coupling of MMICs including on-wafer measurements without via holes.

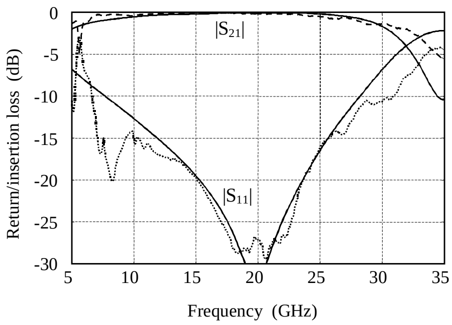

Fig. 13: Theoretical (solid lines) and experimental (dashed lines) results of the transition from the on-wafer probe to a microstrip line without via holes (Alumina substrate, h = 0.254 mm).

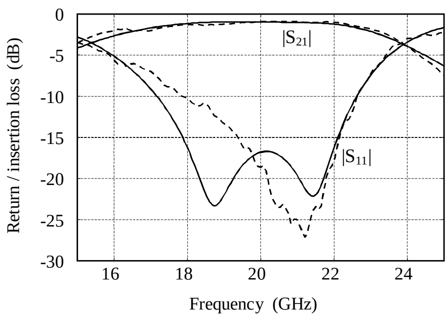

Fig. 14: Theoretical (solid lines) and experimental (dashed lines) results of an electromagnetically coupled transition from microstrip line to coplanar line on a carrier substrate (Carrier substrate: alumina, h = 0.635 mm).

Using MMICs based on coplanar lines, different interconnect techniques have to be chosen. In [23], some investigations have been done to use wire bonding for coplanar lines, too. Much better results can be expected using flip chip mounting of the MMICs. Some precautions, however, are necessary with this technique, too:

- The bumps should be high enough to reduce an interaction with the carrier substrate [24], [25]. Except for the contact pads, no metallization should be on the carrier substrate under the MMIC circuit. Typical bump heights are 25 ... 30 μm for a coplanar line slot width of 15 ... 20 μm.
- In the mm-wave range, the lateral dimensions of some MMICs are in the range of a wavelength. In this case, surface wave resonances may occur and affect the circuit performance. A possible solution to this can be a thinning of the MMIC substrate [24].
- Some precautions have to be taken if the carrier substrate with coplanar interconnect lines has a backside metallization; this may lead to power leakage and cross talk between different parts of the RF front-end [24] - [26].
- A special problem in conjunction with flip-chip mounting is the heat removal of power devices. In this case, additional heat bumps directly contacting the source area of a FET are investigated [27], [28]; some problems, however, may occur with the decreasing size of the transistor in the mm-wave range.

5. Waveguide filters and diplexers

For the front-end according to section II, two standard H-plane waveguide band-pass filters combined with a 3 dB coupler were designed for the LO paths (Fig. 15), and a modified filter arrangement was chosen for the diplexer (Fig. 16). 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 [16]. 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. 17 gives design and measured results of the diplexer machined from aluminum. The design was performed on the basis of a mode matching calculation [29]. The diplexer shows an insertion loss of about 0.6 dB and a rejection of better than 60 dB in the respective other passbands.

For a low-cost, high volume fabrication, plastic injection molding combined with electroplating is an attractive way to fabricate the waveguide circuits. The photographs in Figs. 15 and 16 already show the LO filter/coupler block and the diplexer fabricated in that way. After electroplating, a fully metallized printed circuit board is soldered to the top of the filters.

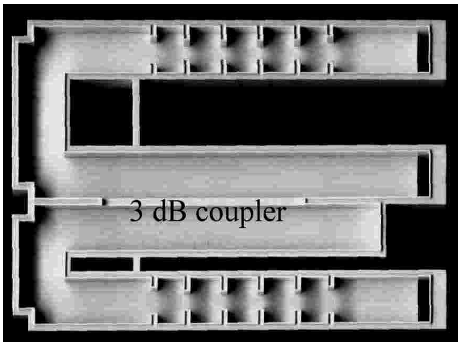

Fig. 15: Photograph of a filter block including two 5 resonator chebishev filters and a 3 dB coupler, fabricated using plastic injection molding. (Waveguide width 7.12 mm).

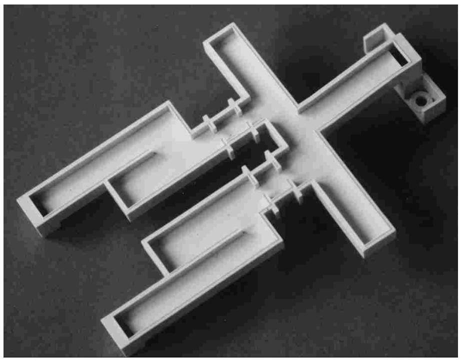

Fig. 16: Photograph of a diplexer fabricated using plastic injection molding. (Waveguide width 7.12 mm).

To cope with the challenges of this production method, some modifications already have to be considered during the circuit 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. 15 and 16) have to be set to the same value – 1.2 mm in this case. In addition, for form stability, the basic filter structure has to be repeated symmetrically below the bottom plate of the filter.

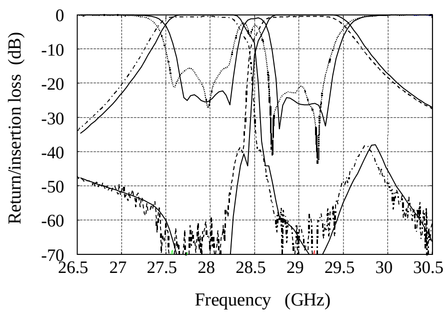

Fig. 17: Theoretical and experimental results of the 28 GHz diplexer machined from aluminum. Solid lines: theory, dashed and dotted lines: experiment).

Further problems with respect to tolerances stem from the production process itself. The shrinking of the injection molded plastic parts during cooling can be precalculated to some extent; this however, is not accurate enough for the fabrication of the filters. The parts fabricated from the same 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. The resulting post heights then are transferred to the form. Once the filters produced with this modified form have an acceptable performance, the reproducibility during production is sufficient. This has been tested both for the LO filter assembly as well as for the diplexer. In Fig. 18, the tuning elements in the filter resonators can be seen.

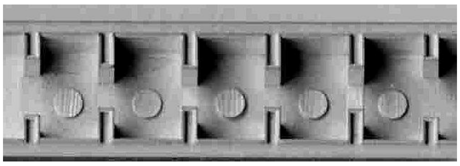

Fig. 18: Photograph of part of the LO filter including matching posts included into the injection molding fabrication process. (Waveguide width 7.12 mm).

Figs. 19 and 20 show the performance of a number of filter circuits fabricated and optimized in a first step of this kind. The original return loss characteristics are not yet completely met, but for many applications, the achieved performance already is satisfactory. Insertion loss for the LO filters (without the coupler loss) is 0.8 dB, and for the diplexers between 0.8 and 1 dB.

6. Conclusion

Different aspects of front-end design, fabrication, and interconnect and packaging techniques for a 28 GHz communication system have been demonstrated. Ribbon bond interconnects are feasible up to frequencies of 20 to 35 GHz, depending on type of transmission lines and geometry. Electromagnetic field coupling favorably can be employed at (higher) mm-wave frequencies, leading to low-loss band-pass type transmission performance without requiring a critical bonding process. Waveguide components like filters, diplexers, or couplers can be fabricated using low-cost techniques like plastic injection molding and electroplating; the involved tolerance problems have been solved by a special tuning procedure required only during the component development, but not after production. Such techniques will pave the way for low-cost millimeter-wave applications.

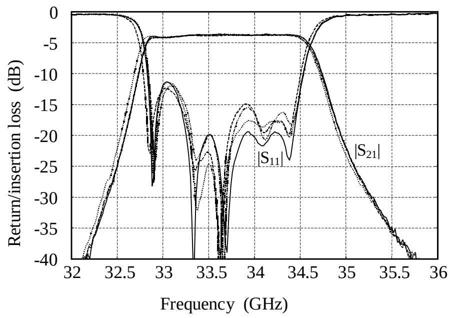

Fig. 19: Return and insertion loss of one of the LO filters after tuning and adjusting the molding form. Four different filter blocks were tested and compared.

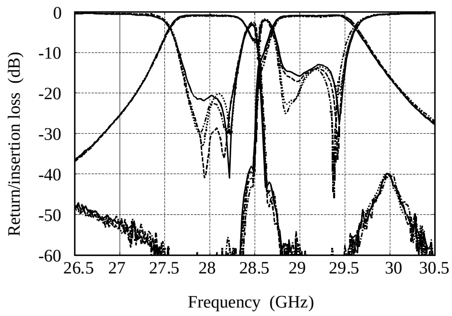

Fig. 20: Experimental results of four different diplexers fabricated by plastic injection molding including the matching structures.

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