# 28GHz Multi-Chip Modules

L.M. Devlin, G.A. Pearson, A.W. Dearn, S. Williamson

Plextek Ltd
London Road, Great Chesterford, Essex, CB10 1NY
Phone: 01799 533 200, Fax: 01799 533 201

## Abstract

*Broadband Wireless Access systems, such as Local Multipoint Distribution Service (LMDS) and Multipoint Video Distribution Systems (MVDS) tend to operate at mm-wave frequencies where large allocations of spectrum are available. These frequencies were previously utilised by low volume applications such as radio astronomy and military systems. The techniques developed and the prices of parts reflected this. As the consumer market for Broadband Wireless Access equipment matures, new techniques are being developed which allow the production of mm-wave equipment in high volumes at low prices. This paper describes the design and development of upconverter and downconverter Multi-Chip Modules (MCMs) suitable for manufacture at low cost, in high volumes. The modules utilise printed filters, GaAs MMICs, discrete SMT components and a PTFE composite soft substrate.*

## Introduction

Equipment operating at mm-wave frequencies was traditionally the preserve of radio astronomy and the military. Systems were produced in low volumes and were normally hand-crafted; as such they tended to be very expensive. Today the use of mm-wave systems for commercial applications is growing rapidly. In particular, broad band multi-media services, such as LMDS and MVDS, have the potential to become very high volume markets for mm-wave electronics. This growth in the commercial use of mm-wave equipment has placed tremendous pressure on suppliers to reduce their costs.

GaAs Monolithic Microwave Integrated Circuits (MMICs) offer a means of fabricating large quantities of highly reproducible, low-cost mm-wave circuits. However, module assembly techniques, suitable for circuits operating at mm-wave frequencies, can be complex and costly. They also tend to be incompatible with low cost assembly methods, which could be adopted for the biasing, control and IF circuitry. This paper describes the development of a low cost route for producing mm-wave sub-system assemblies. A PTFE substrate is used, rather than ceramic and the attachment of bare die and SMT components can be performed in a single process step. Details of the design, fabrication and measurement of a 27.5 to 29.5GHz upconverter and a 27.5 to 29.5GHz downconverter, developed using these techniques, are presented.

### Substrate Manufacture

Careful choice of substrate is vital. As well as being low cost, the substrate should possess the following properties for optimum use at mm-wave frequencies:

- Thin substrate height (to reduce dispersion and radiation losses)
- Low dielectric constant (helps reduce effects of tolerance variations and avoids dimensions of distributed structures becoming impractical)
- Well controlled dielectric constant (reduces performance variation)
- Low dissipation factor (low loss)

With these factors in mind, the material chosen was Rogers RT Duroid® 5880; a glass microfibre reinforced PTFE composite, with a dissipation factor (tan δ) of 0.0009 and a relative dielectric constant

($\varepsilon_r$) of 2.2 (standard tolerance of ±0.02). It is also available in thin substrate heights and 0.005” was selected. The material is also available with brass backing. As well as providing mechanical rigidity, this allows bare MMIC die to be mounted in to pockets cut in to the substrate. This results in the surface of the die being almost level with the surface of the substrate, so minimising bondwire lengths.

The first stage of the substrate processing is the drilling of through substrate via holes and any fixing holes. Selective plating of the through substrate via holes, to contact the front side metallisation with the back, then takes place. Next the pockets are cut into the substrate, revealing the brass backing. Selective nickel gold plating of the copper tracking and the brass of the pocket bases, provides protection from contamination and a surface suitable for gold wire bonding.

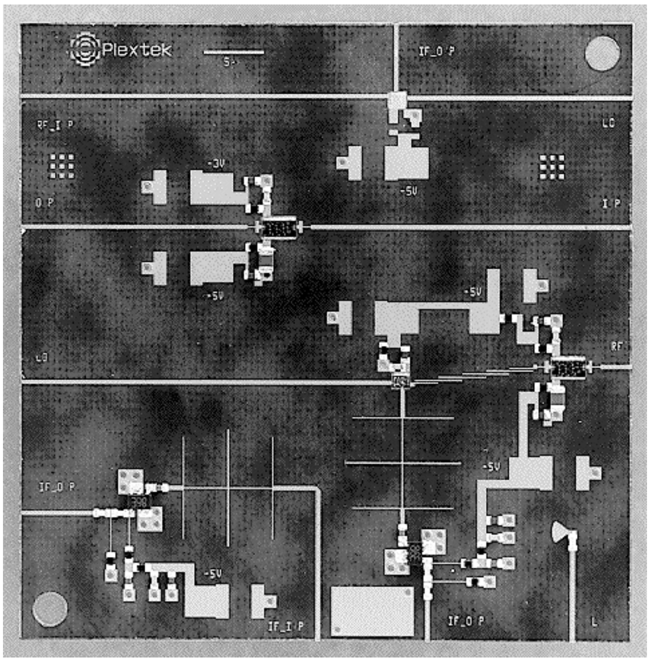

**Figure 1: Photograph of downconverter MCM**

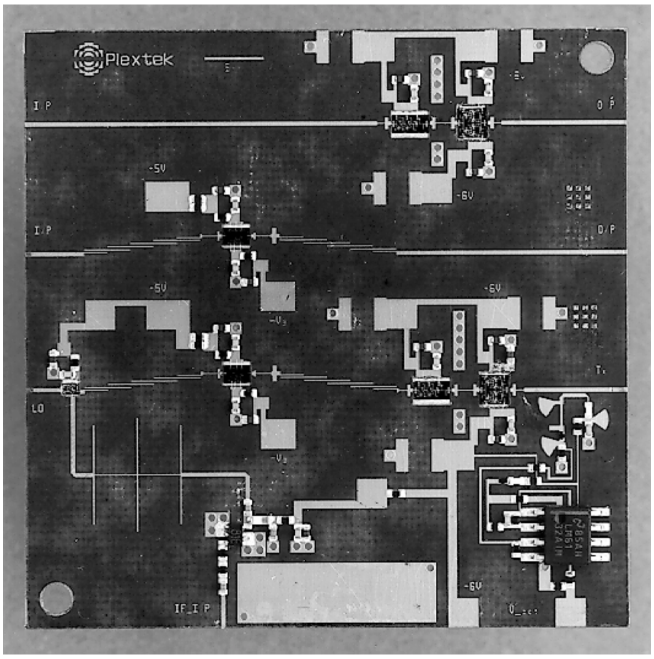

**Figure 2: Photograph of upconverter MCM**

**Assembly**

The first stage in the assembly process is to dispense conducting epoxy in to the pocket bases for die attachment and onto the placement pads for the attachment of any SMT components, which are used. For development work dispensing is carried out manually but automated dispensing methods would be used for volume manufacture. Both the bare die and the SMT components are then placed. Once again this is done by hand during development but would utilise automated pick and place machinery in production. The epoxy is then cured, fixing all components, bare die and SMT, in place in one step.

After curing the die are bonded to tracks or pads on the Duroid using 0.001” diameter gold wire. Wedge-wedge thermosonic bonding is used. Figure 1 shows the completed assembly of the 27.5 to 29.5GHz downconverter MCM. Some diagnostic sub-circuits have also been fabricated on the same tile. No discrete microwave capacitors were used, all de-coupling is realised using 0402 SMT components. This reduces component cost and assembly complexity.

A photograph of an upconverter MCM (which also includes some diagnostic sub-circuits) is shown in Figure 2. The 4GHz IF amplifier and the RF power detection circuit have been realised entirely with SMT components and can be seen at the bottom left and bottom right of the photograph, respectively.

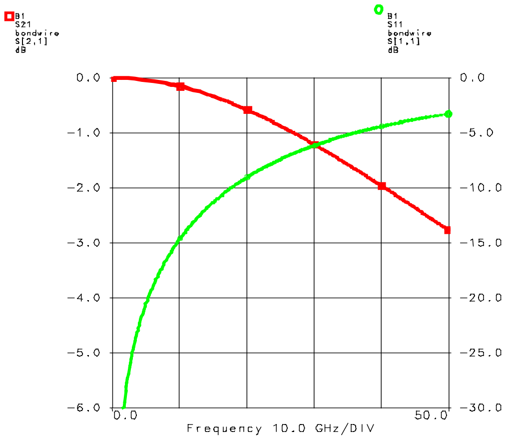

**Figure 3: Insertion loss and match versus frequency for a 0.3nH bondwire**

### Compensating for Bondwire Inductance

Although the fabrication procedure used results in the shortest bondwire lengths, which are practical, there is still an associated inductance of around 0.3nH per bond, for 0.001” diameter wire. At lower frequencies the reactance this represents is very low and can be ignored. At mm-wave frequencies even such low inductances as this can cause significant performance degradation. Figure 3 shows a plot of the simulated insertion loss and match of a 0.3nH bondwire versus frequency, in a 50Ω system. The return loss of the bondwire has fallen to below 10dB by 18GHz and to below 7dB by 28GHz with an associated insertion loss of more than 1dB.

It is clear that simply accepting the performance degradation caused by a 0.3nH bondwire at mm-wave frequencies is not acceptable. There are three options for resolving the problem:

1. Reduce the inductance by using multiple parallel bondwires or gold tape.

2. Use ICs which have been designed to accommodate a 0.3nH inductor at all RF ports.

3. Incorporate the inductance into a low pass filter structure.

Option 1 is not the best approach for low cost, high volume use. Multiple bonds increase assembly time and require a larger, non-standard bondpad (with more parasitic shunt capacitance) and tape bonding has a significant cost penalty. Option 2 is viable but requires all ICs to be designed for a specific assembly process. Also the RF On Wafer (RFOW) measured performance of the ICs will differ significantly from the in-circuit performance as the RF port bondwire inductance, which the circuit’s performance has been optimised to include, would be missing. Option 3 allows ICs designed for best RFOW performance to be used. So long as the bondwire inductance is low enough, it can be absorbed into a practical, low pass filter structure, such as that shown in Figure 4. The printed open circuit stubs act as a shunt capacitance and the narrow (high impedance) series microstrip line serves as an inductance to complete the third order low pass filter structure.

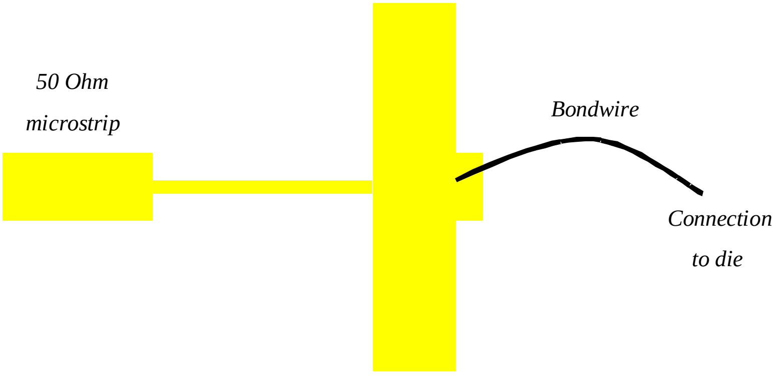

**Figure 4: Low pass filter incorporating bondwire inductance**

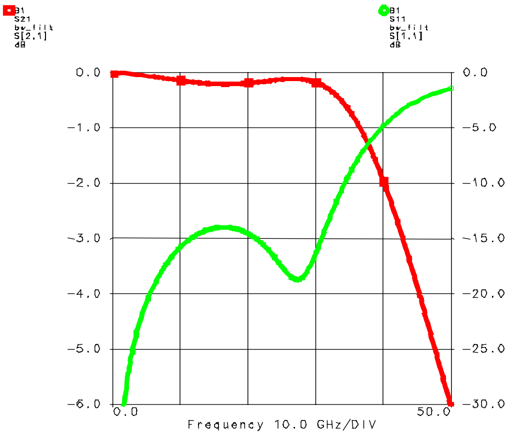

**Figure 5: Simulated performance of a low pass filter incorporating 0.3nH bondwire inductance**

Figure 5 shows the simulated performance of a low pass filter design, which uses this technique to incorporate a 0.3nH bondwire inductance. It has been optimised for use up to 30GHz and improved return loss and insertion loss, as compared to the simple series bondwire case, is evident above 10GHz.

## Downconverter Measured Performance

A downconverter MCM has been designed and fabricated using the methods described above. It operates over an RF frequency range of 27.5 to 29.5GHz, with an IF of 4GHz. The LO input is in the range 11.75 to 12.75GHz, as the downconverter utilises a sub-harmonic mixer which accepts a half frequency LO. All components used are commercially available. A block diagram of the complete downconverter is shown in Figure 6.

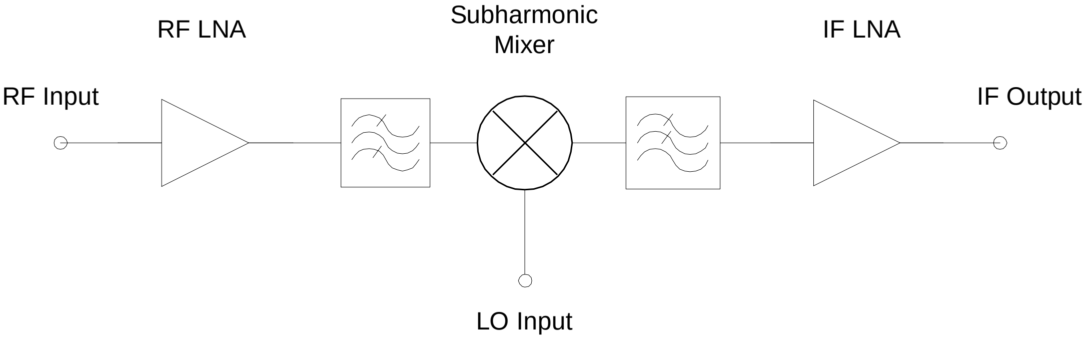

**Figure 6: Block diagram of downconverter**

The LNA and the mixer are both 0.25μm gate length Pseudomorphic High Electron Mobility Transistor (PHEMT) MMICs, which are used in bare die form. Image filtering is realised using a five element, printed coupled line filter [1], whilst the low pass IF filter is a printed stub design. It is strictly a band-stop filter, which rejects the half LO output of the mixer, which can be particularly high for sub-harmonic mixers. An inexpensive SMT component is used to realise the IF amplifier, with a network of 0402 passives and printed stubs to flatten the gain versus frequency response.

In addition to the complete downconverter, a number of sub-circuits were fabricated on the same tile for diagnostic purposes. Figure 7 shows the measured performance of a sub-circuit comprising the IF low

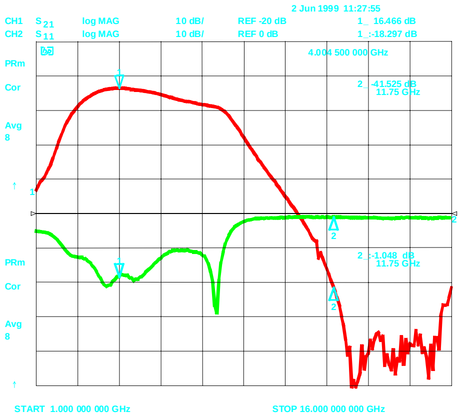

**Figure 7: Measured performance of LPF and receive IF amp.**

pass filter and IF amplifier. It exhibits a gain of 16dB at 4GHz and a rejection of over 55dB for the 11.75 to 12.75GHz half LO frequency range. The conversion gain, versus frequency of the complete downconverter is around 23dB, as shown in Figure 9. Image rejection is over 35dB, across the band.

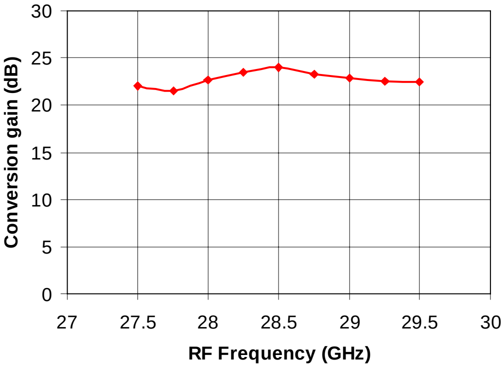

**Figure 8: Measured conversion gain versus frequency**

A plot of the IF port output spectrum for an RF input of -40dBm is shown in Figure 10. The sub-harmonic mixer contains a half LO amplifier and the level of unfiltered half LO at the IF output of the mixer is around +4dBm. This is quite significant and is the reason for the bandstop nature of the IF filter. The half LO level at the output of the entire downconverter is -39dBm, having been substantially attenuated by the IF filter. The quarter LO products are a result of quarter LO output from the signal source used to drive the LO. If this frequency component is present in the end system, a simple high pass filter on the LO port of the mixer can be used to provide attenuation.

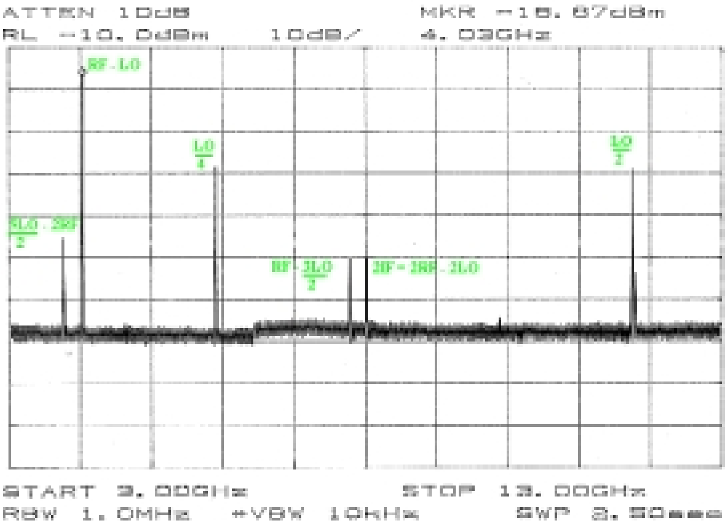

**Figure 10: Measured IF output spectrum**

### Upconverter Measured Performance

Like the downconverter, the upconverter adopts a heterodyne architecture and uses only commercially available parts. Figure 11 shows a block diagram of the upconverter, which uses the same sub-harmonic mixer as the downconverter. All of the transmit chain RF amplifiers are 0.25µm gate length PHEMT MMICs, in bare die form.

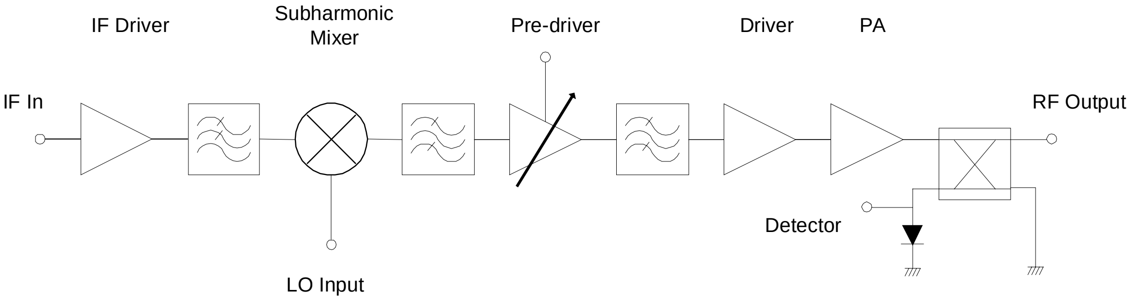

**Figure 11: Block diagram of upconverter**

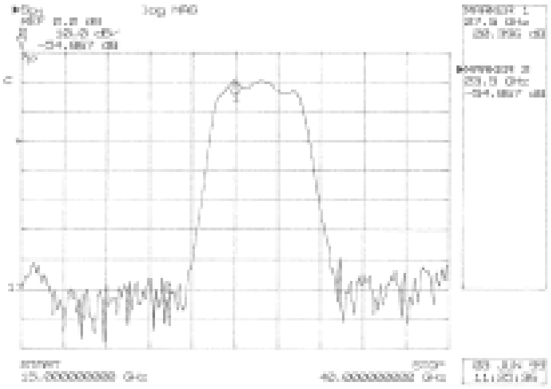

**Figure 12: Measured nominal gain of pre-driver and two printed BPFs**

The IF amplifier and low pass filter are similar to those in the receiver, although an amplifier with higher intermodulation performance is used. Upconverters for LMDS systems, operating in the 28GHz band, are likely to use non-constant envelope modulation schemes and good transmitter linearity will be important. Some system developers are also considering higher order modulation schemes, such as 16-QAM (Quadrature Amplitude Modulation), where the requirements for linearity will be even more stringent in order to preserve modulation fidelity.

The unwanted sideband output from the mixer (LO-IF) will be at around the same level as the wanted RF signal (RF = LO+IF). The LO output will also be at a significant level and these, together with any other unwanted spurious outputs must be heavily attenuated prior to final amplification. Two five element coupled line band pass filters are used, one either side of the variable gain pre-driver, Figure 12 shows the measured performance of a sub-circuit containing this structure. The image and LO rejection is over 70dB.The variable gain amplifier has a gain control range of over 15dB and can be used to adjust the post mixer gain to optimise linearity or compensate for gain variation with frequency or part to part. The overall conversion gain of the entire upconverter is around 43dB. Figure 13 shows the measured power transfer characteristics with a 1dB gain compressed output power level of +23dBm.

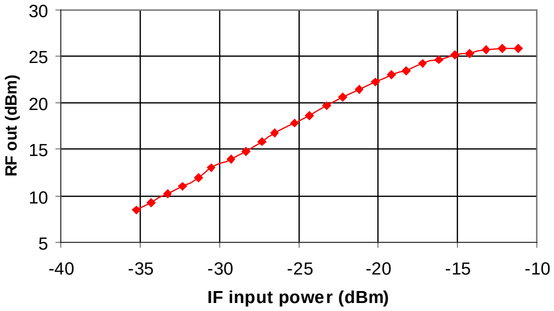

**Figure 13: Measured power transfer characteristics of entire upconverter**

## Conclusions

A low cost process for manufacturing mm-wave modules, which is suitable for automation in volume manufacture, has been developed. A PTFE composite substrate is used, with mm-wave MMICs and SMT components assembled in a single process step. Two 27.5 to 29.5GHz MCMs, a downconverter and an upconverter, have been designed, manufactured and measured. The downconveter has a conversion gain of 23dB with 35dB of image rejection. The upconverter has a conversion gain of 43dB with a 1dB gain compressed output power of +23dBm. All of the components used are commercially available.

## Acknowledgement

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## References

[1] S. Williamson and A.W. Dearn, “Low cost microstrip filters and mixers at 43GHz”, Proceedings of the IEE Colloquium on MM-Wave Circuits and Technology for Commercial Applications, Wednesday 24th March 1999, pp 3/1-3/8