A 47-GHz LNA

MMIC Experiences on the 6-millimeter Band

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Daniele, IW0FGR, and I thought that we needed to improve our stations by increasing the receiver and transmitter performance with an increase in output power and a reduction in receiver NF. We reached this conclusion after some intense activity on the 10-GHz and 24-GHz bands and a shy attempt on the 47-GHz band with no contacts and with just two transverters based on a sub-harmonic mixer design.

Tackling such high frequencies is not easy, and difficulties increase exponentially for the following reasons:

- Lack of suitable materials and components
- Lack of knowledge of the involved technologies, which differ greatly from those used by the majority of operators (on HF)
- Lack of equipment necessary for calibration and measurement

We needed to start by looking for the necessary active devices available on the market, which could be used by us hams. We found that as the frequency increases, the availability of discrete active devices such as transistors (in both packaged and die forms) decreases. Instead, MMICs (Microwave Monolithic Integrate Circuits) are becoming more and more commonplace, as they are in the lower-frequency bands. For example, the ERA and MAR MMICs from Mini-Circuits Labs. Yet, there are certain difficult problems that need to be overcome to succeed in the millimeter-wave bands. The products present on the market have the following drawbacks for use in ham bands :

- The working frequency ranges for which these devices are optimized are about 10-20% of the center frequency and cover (rightly) the fre-

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quency bands of the telecom and military markets. The 10-GHz and 24-GHz ham bands are the most fortunate, but it is not so for the 6-mm band (47 GHz) or higher frequencies (77 GHz).

The MMICs on the market that can guarantee interesting performance are all in the die form, which means we have no choice but to tackle new technologies and their specific requirements (wire bonding, epoxy attach, handling and storage of die MMICs).

Before going any further with our experiences and realizations it is important to explain some of the technical problems and technologies that we had to face.

Handling of MMICs

MMIC Storage

Die MMICs are usually shipped in special containers, such as GEL-PAK trays (visit **www.gelpak.com**) or Wafflepack trays (visit **www.ictray.com**). These should be stored in a temperature- and humidity-controlled area, preferably under a dry-nitrogen flux. The latter aspect is important in GaAs MMICs if their surface is not passivated with NSi4, since hydrogen molecules that are adsorbed into GaAs tend to change its electrical characteristics and modify the devices' functional characteristics.

GEL-PAK is in any case not recommended for long-term storage (typically greater than 1 year) due to possible chemical interactions between gel and the backside metallization of the die which can bring problems in attaching the device. In case it is necessary to store chips for a long time, it is better to have them delivered in Wafflepack trays.

All of this is very complicated for us hams, and for the majority of us practically impossible.

"It's so small! How do I pick it up?" Well the answer is easy: A pair of clean stainless tweezers are sufficient. Take care to pick up the die in a correct way, to avoid chipping the upper edge of the die (see Fig 1). We recommend buying tweezers from Dumont (visit **www.etweezers.com/**) or Fontax.

ESD

High-frequency GaAs devices are, for obvious reasons, usually not designed with on-chip ESD protection circuitry. Due to their reduced geometry sizes, MMICs are very sensitive to ESD degradation or failure. It is necessary to observe the same rules used for Class 0 silicon devices.

Assemblies with die MMICs

Die Attachment— General Guidelines

There are two methods for attaching a die to a substrate or a metal base (see Fig 1A). The choice is generally determined mainly by the devices' thermal-dissipation requirements, though attaching the die to a metal base is the best solution to simultaneously achieve a good RF ground and thermal cooling. The two methods are conductive die attachment and eutectic die attachment.

The general guidelines are:

- Low-power devices can be attached with a silver-loaded epoxy.
- Medium-power devices can be attached with a silver-loaded organic adhesive (30-60W/mK, millikelvins) or epoxy (2-3W/mK), but this should be limited to devices mounted in low-temperature environments.

The recommended method is suitable for both medium and high-power devices. They should be attached with eutectic solder, such as (80/20 Au/Sn).

It is possible to attach low-power devices directly onto substrate materials (see Fig 1B), but take care to provide a low RF ground inductance under the die chip and avoid non-TEM propagation modes or spurious oscillations will result. This can be accomplished by including via-holes though the substrate (see drawings).

Epoxy Die Attachment

Epoxy die attachment is the standard industrial method. It has lower production costs with good reliability of the finished product. From a physical point of view, epoxy attachment is based on Van der Waals interaction rather than atomic or molecular in-

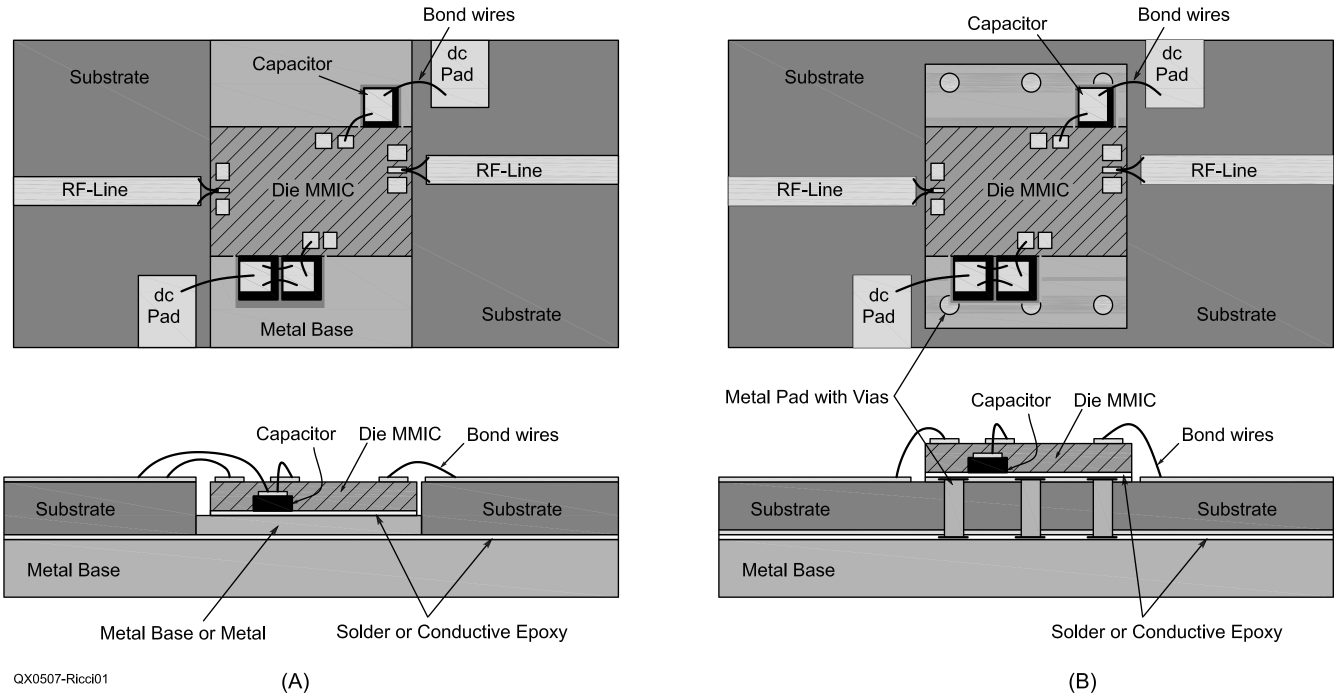


Fig 1—Die installation on metal (A) or substrate (B).

teraction. Epoxy is therefore an adhesive paste composed of two components, silver or gold grains filled epoxy and a hardener, mixed together and deposited in liquid form on the surfaces which are to be attached. The epoxy Curing times depend on temperature. It can be done at room temperature, but it is generally better to do it in a ventilated oven at, for example, 90°C and will take about an hour and a half.

Conductive epoxy can be bought as:

- One-component epoxy (hardener is shipped premixed with epoxy). This is a ready-to-use product, but to slow polymerization, it must be stored at low temperatures (–40°C), but even in these conditions, its average useful life (pot-life) is approximately 6 months;
- Two-component epoxy, which must be mixed prior to use. The mixing procedure and ratios are indicated by the manufacturer, and they must be performed in a clean, dry environment. The unmixed components can be stored at room temperature, with an average storage lifetime of one year.

To achieve a good attachment, it is imperative to clean the dispensing equipment and metal-base chip carriers (metal or substrate) with isopropyl alcohol to eliminate possible contaminants. The epoxy can be applied manually, with a needle.

It is very important to minimize the thickness of the epoxy layer. First, to keep thermal resistances low. (Take care to avoid air bubbles and gaps!) Second, to avoid short circuits caused by the conductive epoxy overflowing the top of the chip or flowing between the chip, substrate and RF lines.

Learn to make the epoxy drop just a little larger than the chip lead, resulting in a narrow fillet around the

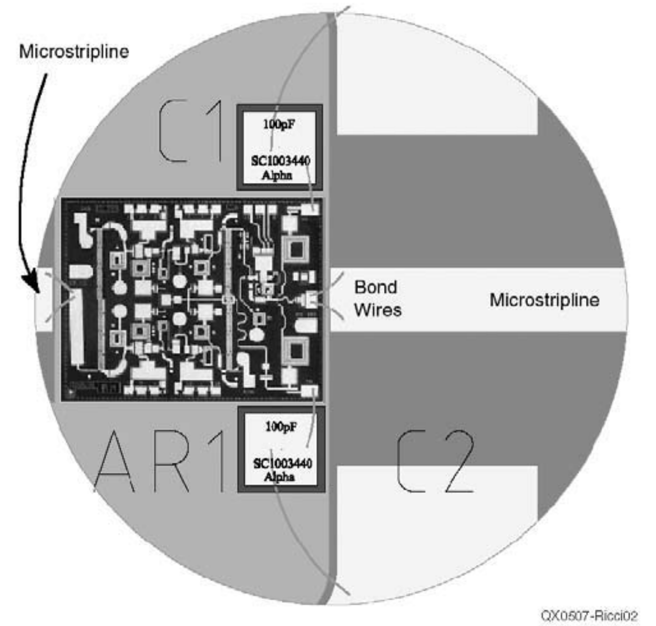


Fig 2—A MMIC with external parts mounted on a circular substrate.

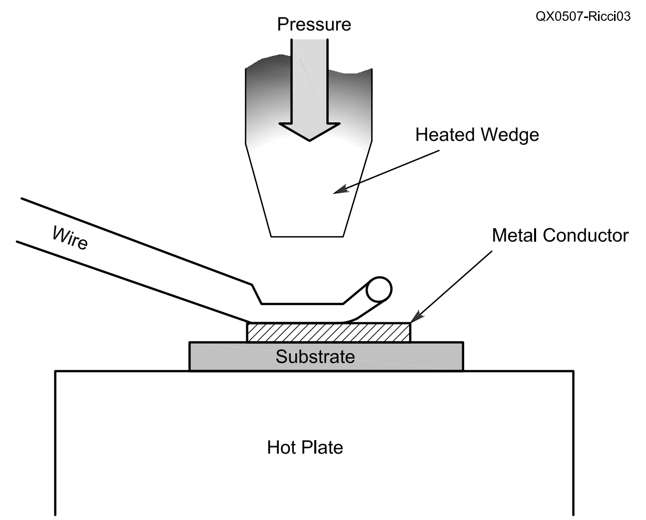
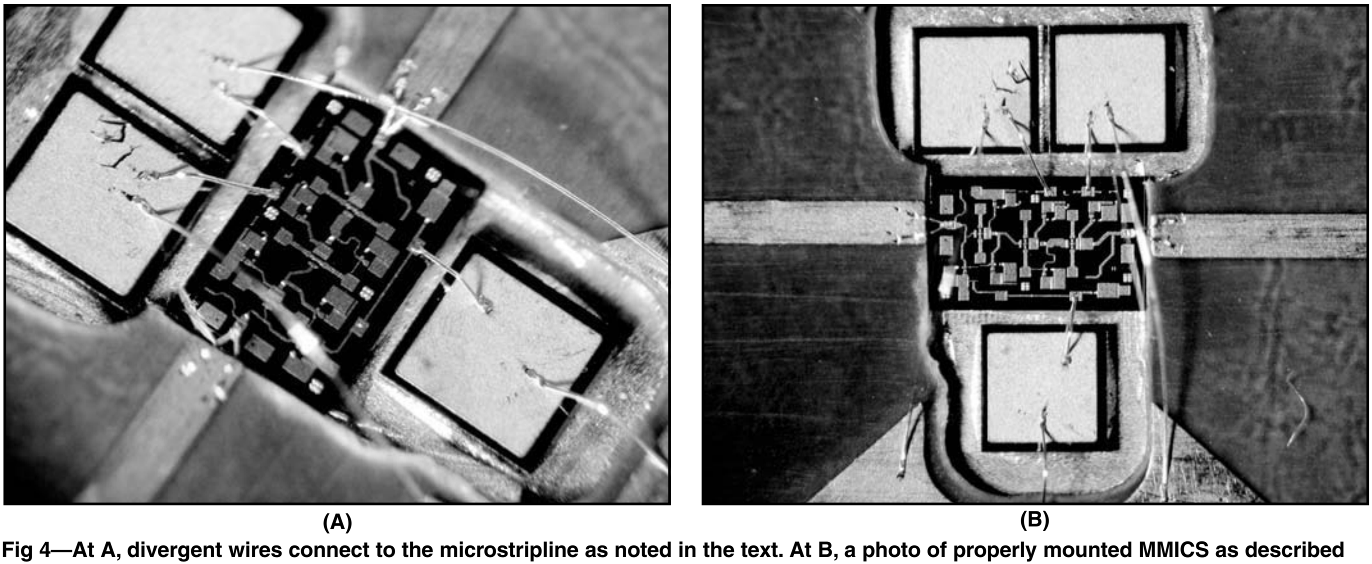


Fig 3—Thermocompression wedge bonding.



(A)

(B)

Fig 4—At A, divergent wires connect to the microstripline as noted in the text. At B, a photo of properly mounted MMICS as described in the text.

contact! Position the chip directly at its final position and press it slightly, making sure not to damage the top surface of the die. Chips have delicate components, such as air-bridges, and spiral inductors, which are damaged very easily.

Here are some references for epoxies:

- EPO-TEK H20E from EPOXY TECHNOLOGY; **www.epotek.com**
- ABLEBOND 84-1LMI from ABLESTIK; **www.ablestik.com**
- DM6030HR from DIEMAT; **www.diemat.com**

QMI5030 from the former DEXTER ELECTRONIC MATERIALS (**www.dexelec.com**); as of August 2003, Dexter was bought by LOCTITE **(www.loctite.com)**.

Eutectic Die Attach

We won't cover this topic section in this article. But maybe next time, when we do some high-power MMIC assemblies!

Bonding

Classic (SnPb) tin-lead soldering is not possible with die MMICs because of incompatibility between SnPb and gold (gold is present on the chip pads and microstrip) and because MMIC dimensions are much smaller (typical dimensions are $\frac{1}{2}$ mm^2) than with other chips. Needless to say, with these very small dimensions it is fundamental to observe everything through a microscope! Other bonding materials and techniques are therefore necessary.

Bond wires

The bond wires used to connect the MMIC to the microstrip lines on the external substrates are usually pure gold, 18 µm to 25 µm in diameter, which have an inductance in the order of 0.6 nH/mm to 0.8 nH/mm. MMIC designs account for the inductance effect of bonding wires in the final chip performance, so it is desirable to strictly adhere to the MMIC designers recommended mounting specifications.

The best way to achieve the electric transition from the coplanar-with-ground structure to the microstrip structure is by using two divergent bond wires as shown in the Fig 4A. This can only be conveniently accomplished with 18 µm-thick wire and by thermosonic wedge-bonding as described in the next paragraph.

This pair of bond wires must be no longer than 200 µm in order have an overall inductance value ranging from 0.2 nH to 0.4 nH.

Bonding Processes

The two main types of bonding processes are:

1. Ultrasonic bonding (very popular in laboratories);
2. Thermocompression bonding (the preferred industrial method) is subdivided into:
   A. Thermocompression wedge bonding (see Fig 3)
   B. Thermocompression ball bonding

Ultrasonic bonding uses ultrasonic energy (typically 60-100 kHz) to increase the plasticity of metals to be bonded. The ultrasonic system of a wire bonding machine consists of two parts: the ultrasonic generator and the ultrasonic transducer. Here is the bonding sequence: First, under the application of force by the wedge tip, a certain amount of deformation occurs in the lattice structure of the bond wire and/or bond surface. Next is a cleaning phase. Ultrasonic energy (with amplitude vibrations of 1-5 µm, much smaller than the bond-wire diameter) makes the wire and wedge move together, creating friction at a constant pressure on the wire and bond interface surface. Shortly, the wire deforms and heats so that welding occurs. (Welding occurs by the diffusion of the wire and bond surface-lattice dislocations.)

Thermocompression uses a combination of heat and pressure to connect the wire between the die bond pad and the microstripline on the external substrate. No melting between metals occurs as the bond comes about by the interaction of atomic forces between the wire and the metal pad.

Thermocompression Wedge Bonding uses a hard heated wedge-bonding tip made of tungsten carbide together with a wire spooler equipped with a wire clamp. The wire is pressed on the bond pad with a controlled force, typically 20 to 22 grams. This process requires a precise alignment of tool force, work stage and tip temperatures.

Thermocompression Ball-Bonding instead has the wire fed through a capillary in the tip, which is heated to a high temperature (300-400°C). A hydrogen flame or spark discharge is produced at the end of the tool to melt the end of the wire and form a small ball. The tool then moves over the bond pad of the die and presses vertically (force is around 30 to 50 grams) the ball on the pad to realize bonding. The tip is moved to the new location (external substrate) and wire is again pressed (no ball is formed in this case) to achieve the new bond and thereafter cut.

Bonding process control should be completed to validate the die attach process control over time (repeatability) by *pull testing*. Pull-testing may be destructive or non-destructive depending on the test method, but we shall not discuss that here.

Substrate Materials for Microwave

Choice of the appropriate microwave substrate material takes into account many factors such as :

- frequency of operation;
- cost;
- thickness;

Table 1—Characteristics of Thermocompression Bonding Techniques

Characteristic	*Wedge-Bonding*	*Ball-Bonding*
Footprint	Very small, 1.5 to 2 times wire diameter	Large, 3 to 5 times wire diameter
Length	Shortest possible	Longer, wire starts off vertically
Wire Size Capability	≥ 18 µm	≥ 18 µm
Speed	SLOW 2 separate alignments necessary; wire needs to be moved exactly under tool end.	
	FAST omnidirectional movement of tip; wire is fed directly under tool end.	

Table 2—Microwave Circuit Materials

Minimum Substrate (mm)	*Copper Available Thickness (µm)*	*Thickness - unplated (µm)*	*ε @10 GHz*	*Loss Tan @10 GHz*	*Dimensional Stability*
Rogers RO4003	127 ±10	17-70	3.38 ±0.05	0.0027	Good
Rogers RO5870	127 Tol. ?	13-35	2.33 ±0.02	0.02	Poor
Rogers RO5880	127 Tol. ?	13-35	2.20 ±0.02	0.02	Poor
Taconic TLY 3	127 Tol. ?	17-35	2.33 ±0.02	<0.02	Fair

Table 3—Measured Results for a Single CHA2094B

Parameter	*Prototype 1*	*Prototype 2*
Gain	14.3 dB	13.8 dB
NF	5.30 dB	4.78 dB

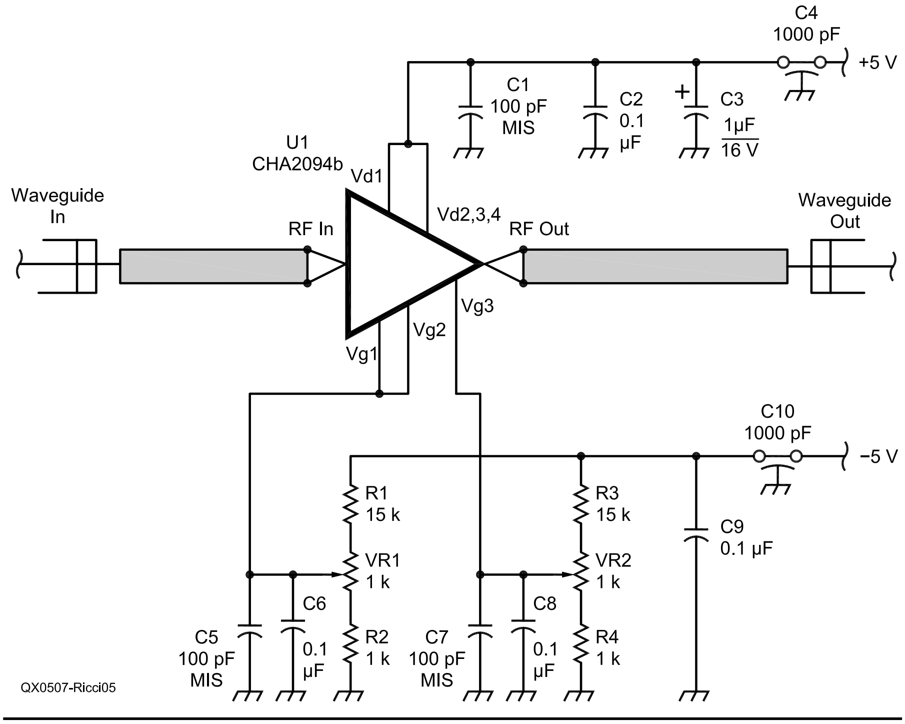


Fig 5—A schematic of the single-MMIC circuit.

- size/Dk;
- dimensional stability.

There is a drawback though. Duroid, though its electric properties are superior to other materials at these frequencies, is unfortunately not the best choice for thermosonic bonding . It is a soft material and the temperatures that are reached in the microstrip region tend to detach the copper strip from the substrate. A harder material would perform better.

Our experiments

At 47 GHz, it is convenient to use Teflon-based copper-laminated dielectric materials (ε>> 2.3, with a flash of gold on the copper of approximately 3 µm to avoid oxidization) 5 mils thick (127 mm). This is not only an electrical necessity (microstrip propagation requires that the height of the dielectric material be many times smaller than the electric wavelength) but also a mechanical necessity. MMICs are usually about 100-127 µm thick, which means that the RF pads of the MMIC are at nearly the same height as the RF microstrip lines. This simplifies bonding, which would otherwise require a “deep-access” bonding tool. It also ensures that the bond wires remain as short as possible, minimizing their total inductance, which turns out to be an electrical requirement, as well.

In this case, a 50 Ω microstrip line is approximately 350 µm wide, while on the MMIC the RF pads are usually about 70 µm wide and usually are *coplanar with ground* lines.

The MMICs meet the following conditions for proper mounting and performance (see Fig 4):

- The low-power MMICs were glued with conductive epoxy (like H20E EPO-TEK) on top of a conductive mechanical holder.
- There are two 50-Ω microstrip lines for the input and output, each at least two electrical wavelengths (in microstrip) to allow for tuning. Tuning was accomplished by moving shorting bars made of copper (with a gold finish). A gold-loaded conductive epoxy, such as H81E (from EPO-TEK) can be used, but it is very expensive! The microstrip lines were glued with a conductive epoxy (such as H20E) to the mechanical holder or at the bottom of the cavity. It is better to obtain some 5 mil 5880 or 5870 Duroid (ROGERS Corp.) that has one side with coated with ½-ounce ED copper and the other side with thick (60 or 90 mil) ED copper. Vendors can provide their dielectric material in such form upon request. This solution is apparently costly, but it does not require a mechanical holder; it has sufficient mechanical strength.

MMICs are typically powered from a 4 or 5 V supply through the FET drains and or more variable voltages to set bias condition of the FET (gates). Typically, this voltage is negative (–5 V). Ensure that the negative bias voltage is applied *before* the positive drain voltage. Otherwise, permanent MMIC damage may result. Refer to the component datasheet for power-supply details.

Power supplies must be carefully

filtered. The filters are usually made of a small inductance (the bond wire forms a RF choke) and an RF-shunt capacitor mounted (epoxy-glued) directly near the power-supply pads of the MMIC. Select appropriate capacitors carefully. MIS (metal-insulator-semiconductor) capacitors are very good capacitors for shunting mm-wave frequencies. It is usually good practice to follow the indications given in the MMIC datasheet, since the MMIC designers account for a recommended power supply and bias circuit when optimizing design performance.

The MMICs We Used

Last year (2002), we were investigating what the MMIC market could offer to hams. The MMIC market is substantially held by a few companies, such as Filtronic, UMS, Agilent, TRW-Velocium, Mimix, Raytheon and TriQuint, Some of these have internal GaAs MMIC foundries, while others are mainly MMIC design houses.

Our research resulted in the choice of two MMIC amplifiers (all datasheets are available through the Internet).

CHA-2094B from UMS: 20-dB gain, three-stage low-noise amplifier (LNA) with a maximum output power of 8 dBm and a NF of 0.75 dB.

HMMC-5040 from Agilent: a four-stage medium power amplifier (MPA) to work in the 20-40 GHz band with a typical gain of 22 dB, a 1-dB compression point of 18 dBm and 21 dBm saturated output power. No further information was available at 47 GHz (S-parameters and so on), but a close look at the gain curve made us feel its performance could be acceptable in our frequency band.

Our Prototypes

Fig 5 shows the circuit we used for our prototypes. The positive (drain) power supply is designed around a 7805, and the gate negative voltage is designed around an ICL7660. The devices require three different bias voltages (input stages need V_{gs1} and e V_{gs2}, V_{gs3} is for the output stage).

The nominal bias current is approximately 20 mA for the output stage and 15 mA for each input stage; for a total power consumption of 50 mA. The best NF performance is accomplished with 45-mA total power consumption.

We have measured performance of the two MMICs in both single and cascade arrangements.

The CHA2094b, alone, yields poorer results (both in NF and in Gain) than we expected based on the datasheet. Even in-band (36-40 GHz) measurements exhibited 5 dB more noise than on the datasheet. This is not justified by the losses of the waveguide-to-microstrip transitions and losses in the input and output microstrip lines.

Anyway, the results in Table 3 were still very interesting. The measured values must be considered average values since they depend on temperature, which we didn't measure.

Table 4 shows the performance for the two modules connected in cascade and to the transverter.

The same preamplifiers have been used in both transmission and reception by means of a WR22 waveguide transfer relay, and the power measurements have given these results:

Input	–6.32 dBm
Output	12.19 dBm, approximately 16.4 mW (near saturation)

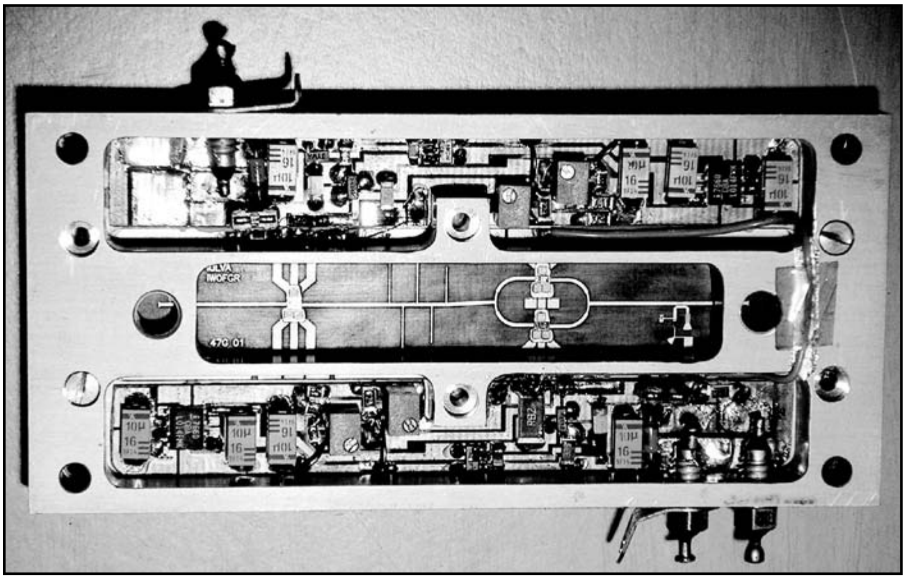
The output shall be used to feed a power amplifier we are designing and we will describe that in our next article.

The output power at the 1-dB compression point, even though it varies with temperature, once stabilized, has been around 10.5 dBm, which is indeed a good result.

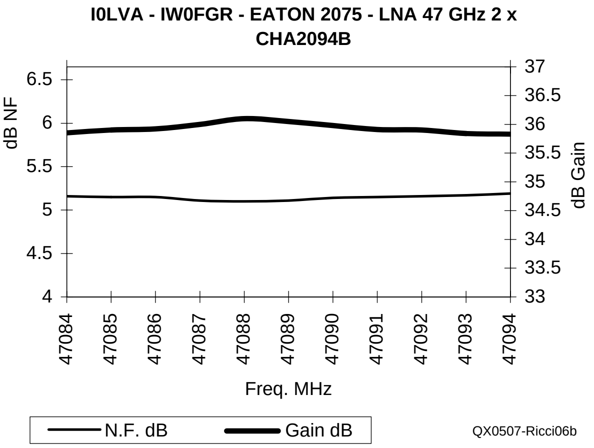
We performed measurements on the cascade of two HMMC-5040 MMICs and the results were a gain >>25 dB; NF ≈ 8 dB; Pout ≈ 15 dBm

Table 4

Parameter	*Prototype*	*Notes*
Gain	26.8 dB	36.1 dB together with the transverter of Fig 6
NF	5.10 dB	
I	90 mA	



(A)



(B)

Fig 6—At A, a photo of the test setup with single and cascade MMICs and a transverter. At B, characteristic curves for the LNA with CHA2094B and cascaded transceiver.

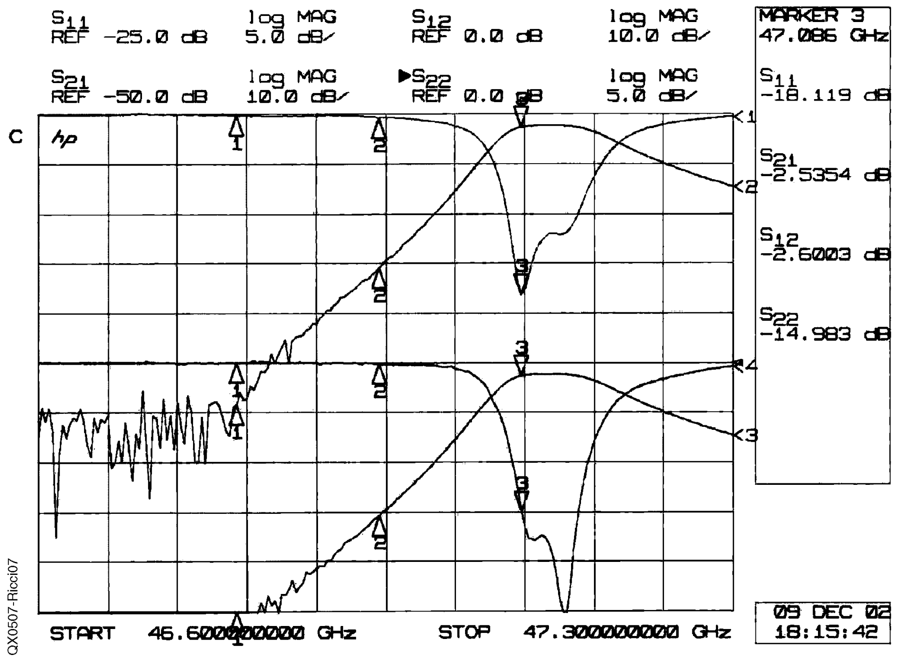


Fig 7—Response curves for the image-rejection filter.

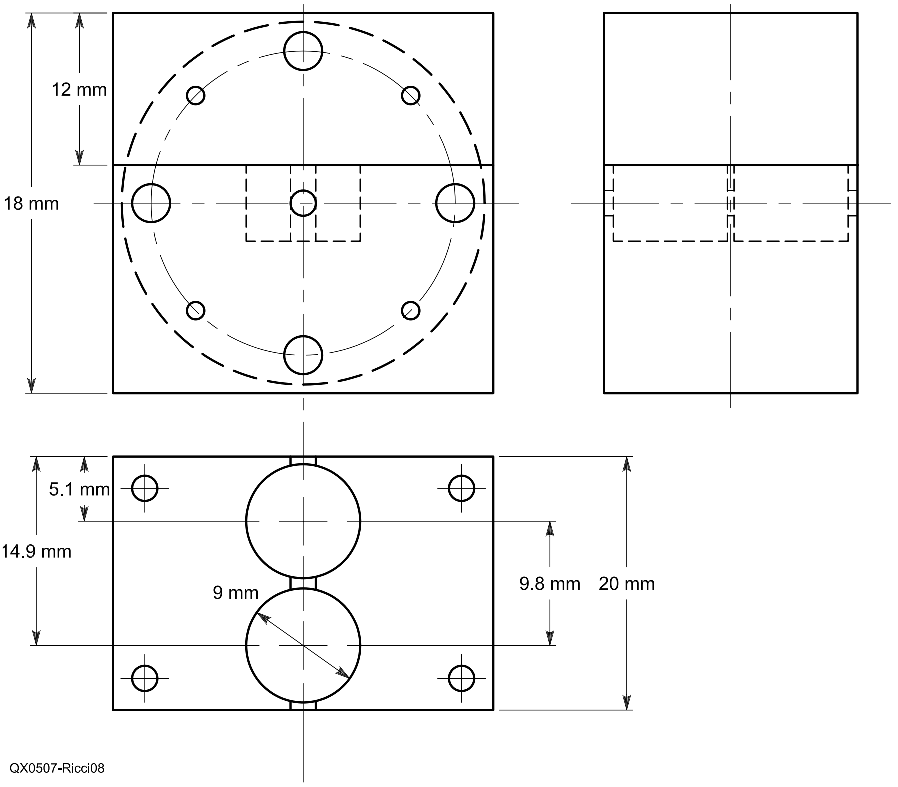


Fig 8—Mechanical details of the image-rejection filter.

and 17 dBm in saturation. The dc power requirement is about 550 mA.

The Image-Rejection Filter

Receiver input noise forced us to use an image-rejection filter in our receiving chain. Here's a brief introduction and description of our approach with this type of filter in the 6-mm band. The filter we used is a doubly coupled resonant-cavity filter designed in a circular waveguide and built by our friend Armando, I3OPW, in brass (with no silver plating or other surface treatment). Once the filter was tuned, our first measurements with a network analyzer showed excessive in-band insertion loss of 5 dB, LO attenuation (46,944 MHz) of 50 dB and >60 dB (beyond the sensitivity of our instrument) for f_{IM} (46,800MHz). By increasing the diameter of the coupling hole, we managed to reduce in-band insertion loss to 2.6 dB (maximum) without too much degradation of the out-of-band attenuation levels (>30 dB for LO and >50 dB for f_{IM}), which is acceptable. These measurements are shown in Fig 7. We believe that better results could be obtained with surface plating of the filter capable of enhancing surface conductivity. Fig 8 is a drawing of the filter.

The Test Bench

The following measuring instruments were used:

Noise Figure Meter Eaton 2075B
Noise Figure Meter HP 8970A
Noise Source HP 346A
Noise Source HP Q347B
Power Meter HP 346A
Power Meter HP 435B
Power Sensor HP8487A

Special Thanks to...

We send a special thanks to our friends who have given us material and moral support.

We are now operational and looking to correspond with other hams to do trials or contests. Our local DX field trials at 47 GHz have produced very good results, but there are still many improvements to be done. A special thanks to M.E.D.S. sas for the assembly of our first prototypes and technical/technological skills and advice.

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