Amplifier Combining for High Power at 13cm

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Abstract

With the availability of surplus RF power amplifiers from 1.9GHz Personal Communication Systems (PCS) capable of producing in excess of 40W per module at 2.3Ghz, producing high RF power output levels for EME operation is simplified. This paper discusses the requirements of and presents some designs for the RF power combiners needed to combine such amplifiers to produce output power levels up to 200W. It does not cover modifications to the RF modules themselves, since this would be specific to the particular items available.

Introduction

This work is directly attributable to the appearance of a quantity of Siemens 1.9Ghz transmitter amplifier cards on the flea market at Weinheim last year. Guenter, DL4MEA, produced some modification details for these particular modules [1], and after some discussions with him, I agreed to look at the design and production of some hybrid combiners. The design, testing and implementation of the combiner modules is discussed in this paper, and sufficient detail is given to allow duplication of the combiners for using pairs and quads of similar modules. Whilst the development work was focussed on the specific modules available, the approach and techniques can of course be applied to any set of nominally identical amplifiers. Indeed, there is no reason why the PCB designs should not be scaled to other microwave bands, especially 23cm and perhaps 9cm, to allow increased power levels.

Design Target

The agreed design target was to produce a system consisting of 4 amplifier modules in parallel, which given the measured performance of a single unit would be likely to produce between 160 and 180 watts out. This would necessitate 2 electrically identical combiners – one to be used as a splitter to provide 4 equal drive signals from a single input, and the other to take the outputs of the 4 modules and combine them into a single output. Fig 1 shows a diagram of the system. Also shown in the diagram is an extra amplifier – this is the driver, and is another of the PCS modules. This is necessary because the gain of each module is approx 6dB (they require 10W in to give between 40 and 45W out), thus each module of the quad will need 10W in, and this means that approx 40W must be presented to the input of the splitter. Thus 5 amplifiers are required for this system. Where amplifiers with higher gains are available, the drive requirements will reduce correspondingly.

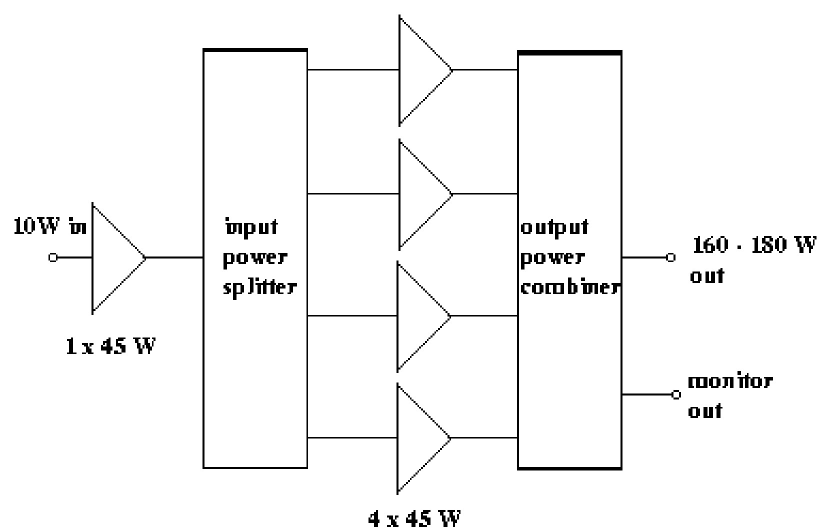


Fig 1 Diagram of Amplifier System

Literature Search

The first activity was a review of the available literature on the design of combiner/splitters – there are many different types documented, with different properties and in different technologies, eg transmission line, in-phase, quadrature, Wilkinson, coaxial, printed stripline, airline etc. Some useful general references are [2 – 4]. And there is a good treatment of the 3dB Quadrature Hybrid in [5]. Since I did my review, an excellent article has appeared in Dubus covering a wide variety of designs [6]. Virtually all of these designs have one common factor – they have one input and two outputs – most also have a load termination port. Thus to achieve a 4 way split would require two successive stages. There was one design that was capable of greater than a 2 way split by W9NUP[7].

This design is capable of a direct 4 way split – however, its downfall was the difficulty of fabrication at 13cm. At lower frequencies where it can be built in coax it would be excellent, especially since it can be used for an n-way split, with simple modifications to change the split ratio.

From the available material, I determined that the 3dB Quadrature Hybrid was the most suitable candidate for the task, since it gave two outputs from a single input, has a termination or load port with minimal power present, is narrowband, but wide enough to accommodate the 13cm band in a single set of dimensions, and can be easily printed. Fig 2 shows the basic design of the hybrid.

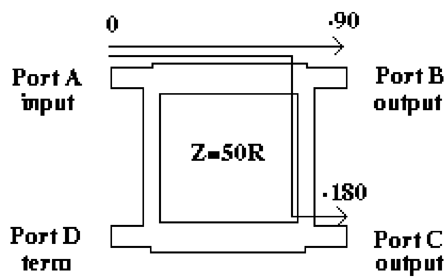


Fig 2 Basic 3dB Quadrature Hybrid, showing phase relationships between port A and ports B and C

With respect to the input at Port A, the output at Port B has a phase lag of 90º, and Port C has a phase lag of 180º - thus there is a phase difference between the output ports of 90º. The signal at Port A is equally split between Ports B and C, hence the signal at each is 3dB lower than the signal presented to Port A. Port D is isolated from Port A (by virtue of the 180º phase difference in the two paths from Port A to D), and must be terminated in a 50R load. Under balanced conditions, there is good isolation, and minimal power is presented to the load – typically the isolation is >40dB. For a 50R Z_O, the line impedances are 50R and 35R5.

In printed stripline form, this hybrid has a bandwidth of approximately 10% of the operating frequency – so at 13cm, a useable bandwidth of approaching 200MHz should be achieved. This is adequate to ensure that a single hybrid design can cover the narrowband, satellite and ATV segments of the band.

A Practical Design

To move from a theoretical treatment to a practical design it was necessary to develop a set of dimensions for the required hybrid, and to make some measurements. The initial design dimensions were derived using PUFF [8]. The substrate for the printed board was selected to be 31 thou (0.79mm) PTFE, as thinner board would handle less power, and the width of the lines for the required impedances becomes difficult to realise at 64 thou. A limitation of PTFE board is that it is not mechanically stable by itself, and for the 31 thou board, the power handling capability is limited to approximately 100W. However, the line dimensions are 'sensible'.

An initial design was evolved, using the simulation capabilities of PUFF to check the predicted performance – the predictions showed that the split of power between the two output ports would not be exactly equal over the wanted frequency range, and also that the phase balance between the outputs would change slowly as well. What it also showed was that the isolation to Port D would be the most critical parameter – the predicted performance indicated an isolation in excess of 40dB, but with a very sharp notch to it – see Fig 3. As can be seen, the change of amplitude is relatively slow, and thus the isolation notch determines the useable frequency range. I decided that for practical purposes, an isolation of =< 20dB was acceptable. This would give a usable bandwidth of around 200MHz, according to the predictions.

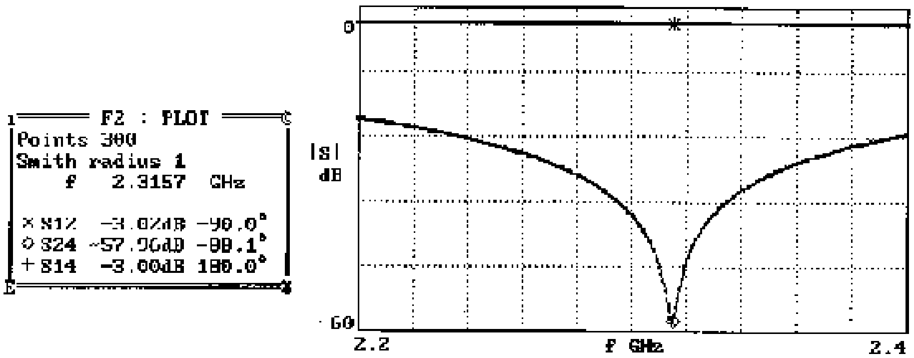


Fig 3 Simulation Results from PUFF

Using these dimensions, an artwork was produced, and some sample hybrids printed up. These were then measured to verify the performance against the PUFF predictions. Table 1 shows the predicted and measured amplitude performance.

	Predicted (dB)	Measured #1	Measured #2	Measured #3
P_{A-B}	-3.02	-3.8	-3.8	-3.8
P_{A-D}	-3.00	-3.2	-3.2	-3.0
P_{A-C}	-58	-18.5	-17.1	-16.6

Table 1 - Predicted and Measured Performance of First Samples

From this it can be seen that whilst the forward power split to the outputs is acceptable (although worse than expected), the isolation is considerably worse than predicted. Although an accurate frequency calibration was not available to me at the time, by comparing against signal generators I was reasonably confident that the display on the HP8620 sweeper was correct, so I decided to investigate where the isolation notch for the hybrid occurred. I discovered that the best isolation was obtained at 2475MHz, rather than 2320MHZ, as designed. At this frequency, the loss to the output ports was -3.2 and -2.8dB respectively, and the isolation was 23dB. This frequency shift was later confirmed on professionally calibrated test equipment at the 13. Vortragstagung, the Munich UHF & Microwave event in March 2000. I was also able to confirm the phase performance of the hybrids on this test equipment.

On the basis of this result, I manually scaled the line lengths given by PUFF to reduce the operating frequency of the hybrid – more samples were printed and tested, and thankfully, an operating frequency of 2320MHz was achieved – the measured parameters of the hybrid are given in Table 2, and the final design dimensions of the striplines (for 0.79mm PTFE PCB, Er=2.55) are shown in Table 3.

	Measured #4	Measured #5
P_{A-B}	-3	-3
P_{A-D}	-3.3	-3.3
P_{A-C}	-29.4	-24.8

Table 2 - Performance of Second Samples

	50R	35R4
Length (mm)	26.56	23.3
Width (mm)	2.00	3.30

Table 3 - Line Dimensions for Second Samples

I have not investigated what the cause of the error in the PUFF design was – it could be in the board parameters specified, although the only parameter that I do not have reasonable confidence on was the thickness of the copper film on the substrate, not having access to manufacturers data for the PCB used. I also did not investigate whether the apparent error in the line lengths also applied to the line widths – a satisfactory performance was obtained by simply scaling the line lengths.

Whilst there are inequalities in the power split of the hybrids, over several samples this inequality is consistent – Tables 1 and 2 both show the performance of different samples printed to the same artwork. Given that the variations in gain between the modules to be used with the hybrids are likely to be greater than the variations shown here, this was considered to be acceptable – in fact a later calculation of the total path loss for each path through a full splitter/combiner proved that the variations cancel each other out – this was verified by measurement, and therefore all paths have equal loss – any variations in the channel gains through the composite amplifier are due to gain variations between the module samples.

Using 2 Modules

Using two of the simple hybrids shown so far two amplifier modules can be combined. The hybrids must be connected as mirror images, to ensure correct phase symmetry through the stage – Fig 4 shows how the terminations and input/output connections must be made. It is essential that all signal paths through the stage have identical (nominal) phase shift in order to achieve the power gain.

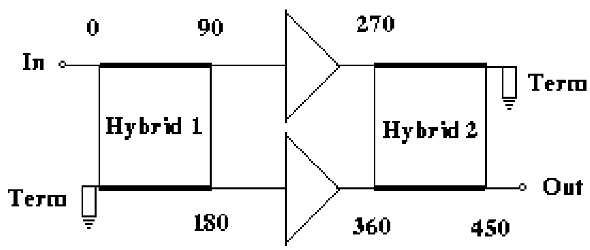


Fig 4 Hybrid Connections for Two Amplifier Modules

Working from the input to Hybrid 1, there is 90º phase lag at Port B, the amplifier gives a further 180º, and the output hybrid a further 180º, giving a total of 450º. Similarly, the path from Hybrid 1 via Port C gives 180º plus 180º for the amplifier and 90º for Hybrid 2 – again a total of 450º.

The Load Terminations

Whilst low power terminations can be used for testing purposes, in a high power application the dissipation of the loads required must be considered. Under normal conditions very little power is delivered to the load port, since there is cancellation of the reflected signals from each output port at the termination port. This feature can be used to help in setting up the hybrid or amplifiers, since connecting a power meter (with suitable protection attenuators!) in place of the termination allows the balance to be monitored while adjustments are made.

Under fault conditions, up to half of the input power to the hybrid can appear at the termination port – thus the load should be specified to withstand that power level. This means that for a two amplifier system, a 10W load is needed for the input hybrid (assuming 20W of drive) and a 50W load is needed for the output hybrid.

Using 4 Modules

With the design as presented so far, pairs of amplifiers can be combined to form higher power stages. By placing another pair of hybrids at each end of two pairs, a four way amplifier can be achieved. Obviously, the three hybrids required at each end can be printed on a single piece of PTFE, provided the correct input and load port allocations are made. There is a problem however – the power handling capabilities of the PTFE substrate. For SSB and CW use operation at around 150W output is probably OK due to the duty cycle of the signals involved – use for FM or ATV modes will almost certainly not be safe at this sort of power level. There are two possible solutions to this:

a) Use an airline hybrid as the final output combiner - a number of designs have been published [3,4,5] and G3WDG has a repeatable design as well. Power handling up to several hundred watts will not be a problem with this approach, and any mode can be used!

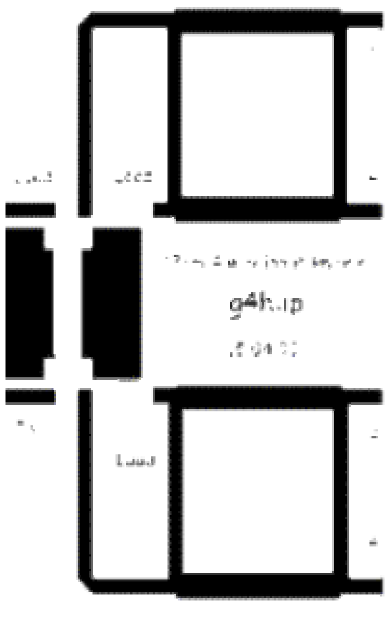
A note on the fabrication of airline couplers – the cutting and trimming of the lines is, of course, critical. Where a published 1:1 artwork is available, printed circuit techniques can be applied! Either UV photographic techniques, using a spray-on photo resist, such as Photolak , or a dry transfer film process, such as Blue Film [9], can be used to transfer the artwork onto copper sheet of the correct thickness. Mask the back side with parcel tape, then put the plate into the etch bath. Keep observing it, and after several minutes (depending on the strength, temperature and age of the fluid!) you will find that the outline of the airline has been etched on to one surface of the copper – this outline will give you accurate lines to cut and file to, and should ensure that with a bit of care you will have a good result.

b) Use Sage Wireline to make a transmission line hybrid – this is sometime found in the flea markets etc. although it is not very common Sage Wireline is rated for either 100 or 200W continuous, dependent upon the diameter of the line. The JC1 material is rated for 200W continuous, 2kW peak – again the proviso of SSB/CW operation applies, although this should be OK for FM/ATV at 200W. Fortunately, I was lucky enough to have access to some, and this was used in my solution. Full design and handling information about the Sage products is available at [10]

Sage Wireline is a pre-formed transmission line product, externally similar to semi-rigid coax cable. The inner consists of two conductors, one of which has a Kapton insulation – this serves both to insulate it from the other conductor, and also to identify it at both ends of the cable.

Sage recommend special tools for stripping their Wireline products – these are not practical for amateur use. I have found that the outer jacket can be removed in the same manner as the outer of semi-rigid coax, eg UT 141 – score all round with a sharp scalpel, then carefully bend to break the outer around the score. Then using the soldering iron, heat up the section of outer to be removed – it will then slide off the dielectric easily. To remove the dielectric from the pair of inner conductors requires considerable care, so as not to remove the Kapton insulation one the one inner conductor. I carefully shave the dielectric from the end back towards the sheath. Shavings can be removed with orthogonal cuts of the scalpel. Do not try to cut through the dielectric and slide it off the conductors, as you would with coax! – You will certainly remove the Kapton as well!

The properties of a transmission line hybrid made from Sage Wireline are quite different to the 3dB Quadrature Hybrid used so far – it still gives a 90º phase difference between its two outputs, but the phase characteristic is much flatter against frequency, making it a much more broadband device. Consequently, to ensure symmetry of the final implementation, I decided that I would use the Sage splitter for both the input and output hybrids. An artwork was then produced combining the Sage Wireline splitter with two 3dB Quadrature hybrids, to make a full 4 way split and combine. Different artworks were produced for each function, since the load terminations are of different power ratings and locations, and the output coupler has a power detector incorporated as well. Fig 5 shows the input splitter artwork, and Fig 6 the output coupler.



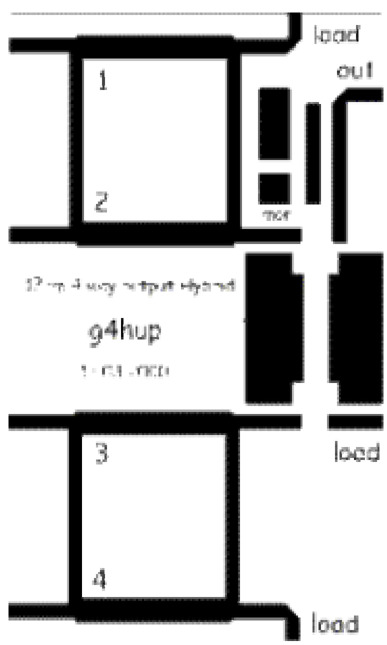


Fig 5 Input splitter artwork Fig 6 Output Combiner Artwork

Measurements on samples of the two splitters were exactly as predicted from the earlier measurements on each of the single stages, including the preservation of the small inequalities between the output ports of the individual couplers. If the path loss of each of the individual paths is calculated, these inequalities cancel out exactly, giving an identical path loss for any route – thus the gain performance of the final implementation is totally dependent on the gain of the amplifier modules used, and therefore the closest gain match that can be achieved with the modules is desirable. This will give the best overall balance (and hence least dissipated power in the loads) of the final implementation.

Termination Considerations for the 4 way splitter

As with the 2 way design, the power at the termination port of each of the hybrids must be considered. Dealing firstly with the input split arrangement, assuming that each module in the amplifier is to be driven with 10W, there must be 20W into each of the two quadrature hybrids, and thus 40W into the Sage hybrid. Thus using the rule given earlier, the termination on the Sage hybrid must be rated for 20W and the other two terminations rated for 10W dissipation each.

On the output combiner, there will be 40W input from each amplifier module, so the terminations of the quadrature hybrids must also be rated for at least 40W. Each input of the Sage hybrid will be carrying 80W, so the termination on here must be rated for at least 80W.

Packaged flange mounted chip terminations were chosen for the terminations at all ports, because they are easy to mount and can handle the power levels required – of course, they require adequate heatsinking for the output combiner, to ensure that they are not damaged in the event of an external fault causing reflections within the combiner. Information and data about the loads used can be found at [11]

Mechanical Engineering of the Design

Everything presented so far discusses the electrical aspects of the design. The mechanical strength of the PTFE substrate has already been noted, and there are other aspects that must be considered in producing a useable unit – eg, the mounting of connectors, screening of the units, and dissipating heat from the terminations under fault conditions.

To achieve mechanical stability for the PCB it really needs to be mounted onto a supporting plate, of aluminium or copper. It was decided that the best way to do this was to design the combiner PCB to fit a standard tinplate box, and to replace one of the lids with a thick aluminium plate – of between 6 and 10mm thick. This plate would provide ample mechanical strength as a support, and it would be thick enough to allow connectors to mounted with screws into the plate, ensuring that any cable stresses are not passed on to the PCB. The only remaining problem is the chip terminations – if they are mounted onto the plate as well, the connector tab will be approx 1.5 – 2mm above the PCB track, resulting in a discontinuity. The solution to this is to use a 2mm thick spacer plate between the main plate and the PCB – this spacer is smaller than the thick plate, and allows the loads to be mounted so that the tabs are flush with the PCB tracks – an alternative, but more complex, approach would be to mill out recesses into the thick plate, so that the loads sit into the plate. Fig 7 shows a diagram of the assembly. M2 screws are used to hold the PCB in place – these screws pass right through the spacer plate, and fasten into tapped holes in the 10mm plate.

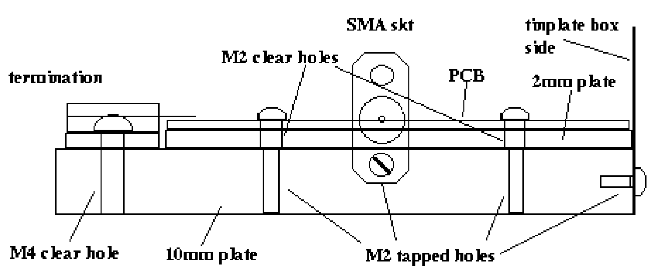
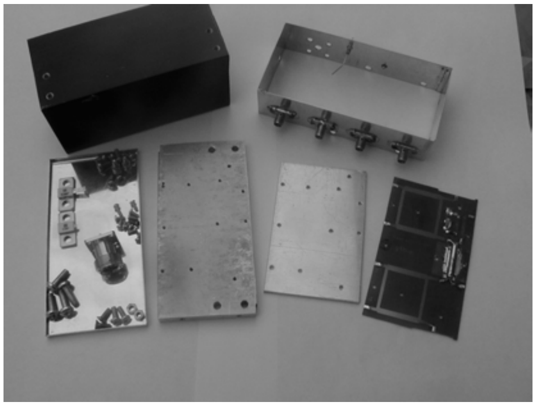


Fig 7 Assembly of PCB, box and plates

In both the input and output combiners, the load port of the Sage hybrid is brought out to a connector, so that an external load can be used, but also so that it can be used as a measurement port during the setting up of the amplifier block. Both combiners, in the Sage line versions are designed to fit into a standard 55 x 114 x 30mm box. Fig 8 shows a photograph of the components of the Sage line version output combiner, and Fig 9 shows it assembled with a heat sink. The M4 screws which secure the two chip terminations in place pass right through the main plate and are into holes tapped in the heat sink. Note that all the SMA connectors on this prototype are shown soldered to the tinplate box – it is recommended that they really should be screwed into the box, as a better grounding method – turn the bodies of the connectors through 90º, and have one screw going into a tapped hole in the bottom plate, the upper one secured with a nut on the inside of the box. This will also reduce the work involved in drilling and tapping the securing holes in the edge of the main plate.



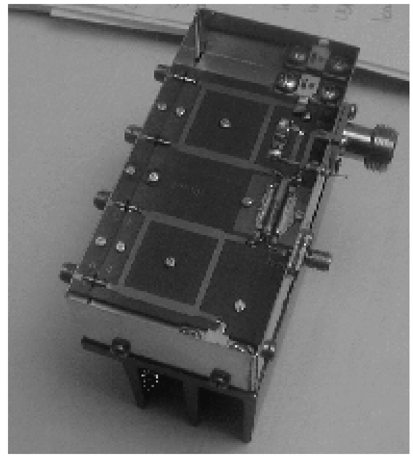


Fig 8 Parts of Output Combiner Fig 9 Engineered 4 way Output Combiner

Although fully engineered prototypes have not been produced yet, the single hybrid, 2 way version is also designed to fit a standard tin-plate box, and identical mechanical techniques can be used.

Other Applications for the 3dB Quadrature Hybrids

There are many documented applications for the hybrid, including creating the phase shifts necessary for circular polarisation in antennas, and in some types of mixer circuits. It is a versatile design, very commonly used as a power splitter within amplifiers, especially in the microwave region, where its dimensions allow it to be conveniently printed as part of the amplifier PCB [12, 13].

Artworks

Due to reproduction and printing processes, no guarantees can be given that the artwork reproductions in this article are accurate. I am prepared to make copies of the artworks available, either as prints or dry transfers for PCB production, but would request coverage of material and mailing costs. I can be contacted by e-mail, dl4mup@qsl.net. Artwork is also available from the author for a version using three printed 3dB hybrids.

References

[1] http://www.qsl.net/dl4mea/13ss/

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[9] http://www.techniks.com

[10] http://www.sagelineinc.com

[11] http://www.emct.com

[12] 10W Power Amplifier for 13cm, Ewald Goebel, DK2DB, Dubus Technik IV, p107

[13] 200mW GaAsFET Power Amplifier for 24GHz, Michael Kuhne, DB6NT, Dubus Technik IV, p146