Wideband isolator

Circulators and isolators are a type of directional coupler with intriguing properties. They are common at microwaves, but they become bulky and expensive at uhf. They would be useful at much lower frequiecies, but they have simply not been available. Ian Hickman's new design covers 0 to 500MHz.

Circulators and isolators are examples of directional couplers, and are common enough components at microwave frequencies. They are three-port devices, the ports being either coaxial- or waveguide-connectors, according to the frequency and particular design.

The clever part is the way signals are routed from one port to the next, always in the same direction. The operation of a circulator – or isolator – depends on the interaction, within a lump of ferrite, of the rf field due to the signal, and a steady dc field provided by a permanent magnet. This is something to do with the precession of electron orbits – or so I gather from those who know more about microwaves. Circulators can be used for a variety of purposes, one of which is the subject of this article.

Figure 1a) outlines a three-port circulator, the arrow indicating the direction of circulation. This means that a signal applied at port A is all delivered to port B, with little coming out of port C. Ideally, no signal will come from port C if the device's 'directivity' is perfect.

What happens next depends on what is connected to port B. If this port is terminated with an ideal resistive load equal to the device's characteristic impedance – usually 50Ω in the case of a circulator with coaxial connectors – then all of the signal is accepted by the termination and none is returned to port B. This means that the 'return loss' in decibels is infinity.

But if the termination on port B differs from (50+j0)Ω, then there is a finite return loss. The reflected, i.e. returned, signal goes back into port B and circulates around in the direction of the arrow, coming out at port C. Thus the magnitude of the signal appearing at port C, relative to the the magnitude of the input applied to port A is a measure of the degree of mismatch at port B.

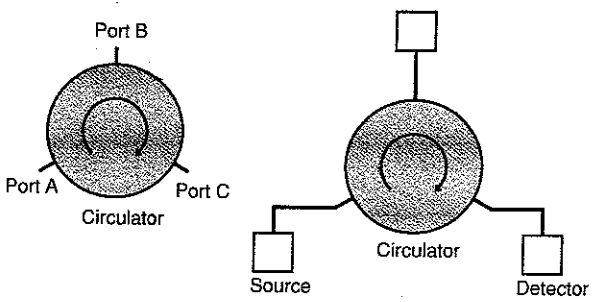


Fig. 1. a) A three port circulator. b) An arrangement using a circulator to measure the return loss of a device under test.

Because of this characteristic, a circulator with the aid of a source and detector can be used to measure the return loss – and hence the vswr – of any given device under test, as in **Fig. 1b)**. This assumes that the detector presents a good match to port C. If not, it will reflect some of the signal it receives, back into port C – from where it will resurface round the houses at port A.

Given a total mismatch, i.e. a short or open circuit at port B, then all of the power input at port A will come out at port C – but strictly via the clockwise route – bar the usual small insertion loss to be expected of any practical device.

Because it is a totally symmetrical device, the circulator in Fig. 1b) could be rotated by 120° or 240° and still work exactly the same. It doesn't matter which port the source is connected to, provided the device under test and detector are connected to the following two in clockwise order.

An isolator is a related, if less symmetrical, device. Here, any signal in Fig. 1b) reflected back into port C by the detector is simply absorbed. It is not passed around back to port A. As a result, an isolator would actually be a more appropriate device for the vswr measuring set-up of Fig. 1b), although for some applications circulators are preferable.

Microwave circulators with high directivity are narrow band devices. Bandwidths of up to an octave are possible, but only at the expense of much reduced directivity. Circulators and isolators are such useful devices, that it would be great if economical models with good directivity were available at uhf, vhf and even lower frequencies. And even better if one really broadband model were available covering all these frequencies at once.

The answer to a long felt need

Though not as well known as it deserves, such an arrangement is in fact possible. It filled me with excitement when I came across it, in the American controlled-circulation magazine *RF Design*.[1]

This circuit uses three *CLC406* current feedback op-amps – from Comlinear, now part of National Semiconductor – and operates up to well over 100MHz. The upper limit is set by the frequency at which the op-amps begin to flag.

What the article describes is nothing less than an active circuit switchable for use as either a circulator or an isolator, as required. It has three 50Ω BNC ports, and operates from, say, 200MHz, right down to dc, **Fig. 2.**

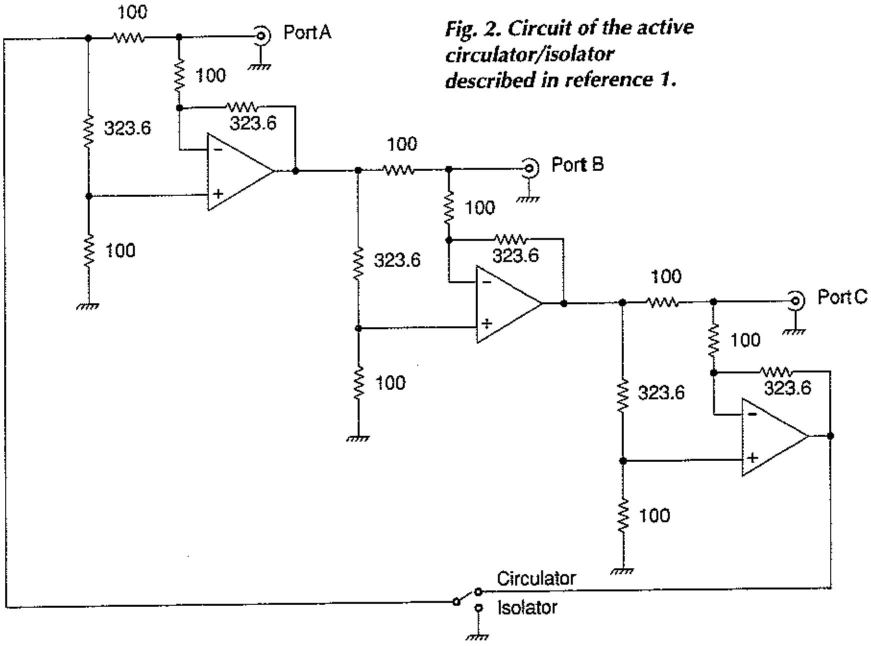


Fig. 2. Circuit of the active circulator/isolator described in reference 1.

While at the leading edge of technology when introduced, and still a good op-amp today, the *CLC406* has nonetheless been overtaken, performance-wise, by newer devices. In particular, the *AD8009* from Analog Devices caught my interest, with its unity-gain bandwidth (small signal, non-inverting) of 1GHz.

Of course, if you demand more gain or apply large signals, the performance is a little less – 700MHz at a small signal gain (0.2V pk-pk) of +2, or 440MHz, 320MHz at large signal gains (2V pk-pk) of +2, +10. Still, it seemed a good contender for use in an up-dated version of the circuit described above.

But before going on to describe it, it might be as well to lyse the circuit to show you just how it works.

How this circulator/isolator works

A feature of this circuit is that it works down to dc. As a result, its operation can be described simply with reference to the partial circuit shown in **Fig. 3.** Here, the voltages may be taken as dc, or as ac in-phase, or antiphase where negative.

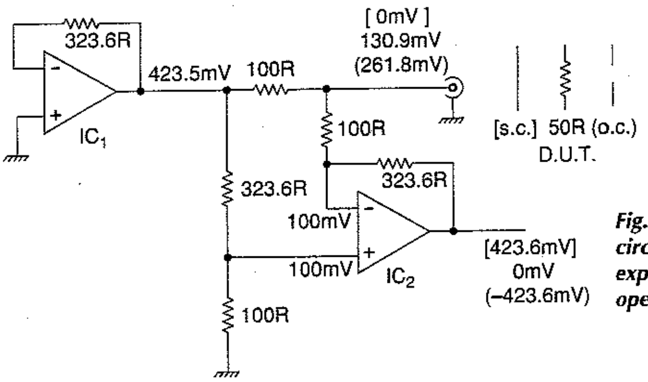


Fig. 3. Partial circuit, explaining circuit operation.

Instead of assuming an input voltage and trying to derive the output voltage, or *vice versa*, a useful trick in circuit analysis is to assume a convenient voltage at some internal node, and work forwards and backwards from there. The results then drop out fairly simply – even by mental arithmetic in some cases.

So assume the voltage at the non-inverting input of IC_2 is 100mV. Then the voltage at the output of IC_1 must be 423.5mV. Also, due to the negative feedback, IC_2's output will do whatever is necessary to ensure that its inverting input is also at 100mV.

Figure 3 shows what the output of IC_2 will be, for the cases of a short circuit, or 50Ω, or an open circuit at the port. The short-circuit case is obvious: the resistor at IC_2's invert- input and its feedback resistor form an identical chain to at at the non-inverting input. Thus the output of IC_2 is at +423.6mV, like IC_1, the overall gain is +1, but note that the op-amp is working at a gain is excess of +3.

In the open-circuit case, the net voltage drop across the two 100Ω resistors in series is 323.6mV, so the output of IC_2 must be at 323.6/200×323.6mV negative with respect to the inverting input. Thanks to the careful choice of resistor values, this works out at −423.6mV.

With a 50Ω termination at the port, a line or two of algebra on the back of an envelope may be needed. Let the voltage at the port be *v*. Now equate the current flowing from IC_1 output to the port, to the sum of the currents flowing from there to ground via 50Ω and to the inverting input of IC_2 via 100Ω.

Voltage *v* drops out immediately, defining the current

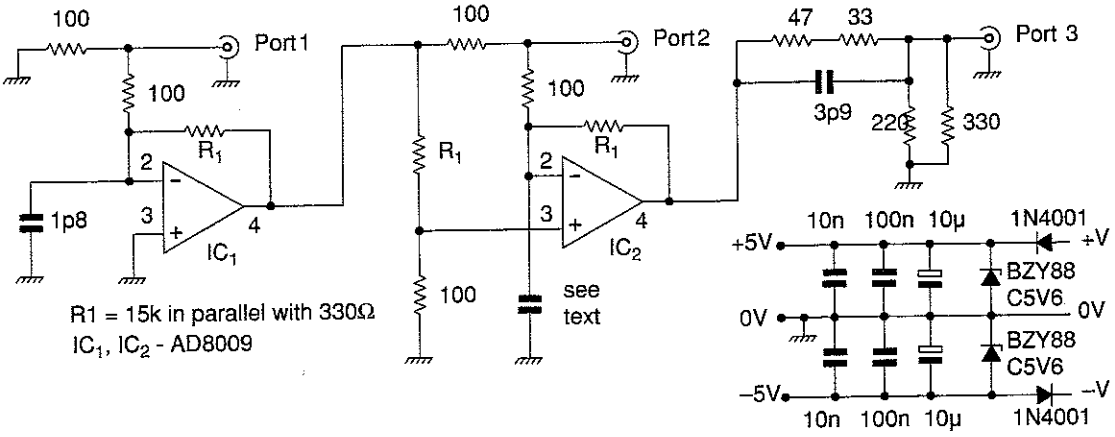
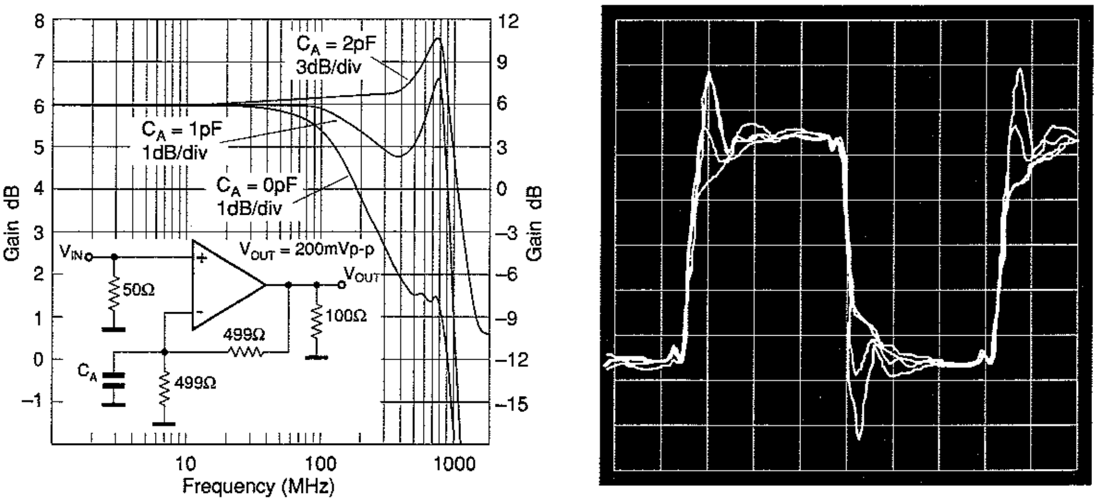


Fig. 4. Circuit diagram of a wideband isolator, usable from 0Hz to 500MHz.

Fig 5a). Bandwidth extension for the AD8009 achieved (for a gain of +2) by adding capacitance from the inverting input to ground.
b) The effect of these three values of capacitance on the pulse response. Horizontal scaling is 1.5ns/div while vertical scaling is 40mV/div.



flowing through the input and feedback resistors of IC_2, and hence the voltage at IC_2's output.

It turns out – again thanks to the ingenious design of the resistive network between each of the op-amps – that the voltage at the output of IC_2 is zero and the corresponding voltage at the device under test port is 130.9mV. Since this is precisely the voltage at a port which produces 423.5mV at the output of the following op-amp, clearly it is the voltage that must be applied to the source input port A – not shown in Fig. 3 – which drives IC_1. Hence the gain from port A to B (or B to C, or C to A) is unity, provided that both the two ports 'see' 50Ω.

Also, if the second port sees an infinite vswr load, the gain from the first to the third port is unity. Effectively, all the power returned from the second port circulates round to the third. At least, this is the case with a circulator.

As Fig. 2 shows, in the case of an isolator, any incident power reflected back into port C is simply absorbed, and does not continue around back to port A.

An updated version

Having obtained some Analog devices *AD8009* wideband current-feedback op-amps, I was keen to see what sort of performance could be achieved with such an up-to-date device. Clearly, it could simply be substituted for the *CLC406* in the circuit of Fig. 2.

But, after careful consideration, it seemed that all the applications I had in mind could be met with an isolator. Now if you are is willing to forego the ability to switch the circuit to operate, when required, as a circulator, then not only are substantial economies in circuit design possible, but also one or two dodges to improve performance at the top end of the frequency range can be incorporated.

So at the end of the day, my circuit finished up as in **Fig. 4**. You can see immediately that as an isolator only, the circuit needs but two op-amps. Also obsoleted are a switch, and a number of resistors, while port C is simply driven by an L pad.

A word about the power supply

But before describing the operation of the rf portion of Fig. 4, a word about the power supply arrangements is called for.

Circuits under development sometimes fail for no apparent reason. This often put down to 'prototype fatigue', meaning some form of unidentified electrical abuse. I have suffered the ravages of this phenomenon as often as most.

The construction of the isolator, using op-amps in small-outline SO8 form, chip resistors and 0805 packaged 10n capacitors, was not a simple task. It involved both dexterity and some eye strain.

I built the circuit using 'fresh air' construction on a scrap of copper-clad FRG used as a ground plane. The thought of having to dive back into the bird's nest to replace an op-amp or two was horrific, so some protection for the supplies was built in.

The series diodes guard against possible connection of the power supplies in reverse polarity, while the zener diodes prevent excessive voltage being applied. The types quoted will not provide indefinite protection from 15V supplies with a 1A current limit, but they will guard against an insidious and often unrealised fault.

At switch-on, some older bench power supplies output a brief spike of maximum voltage equal to the internal raw supply voltage. And after a number of years' use, many power supplies develop a noisy track on the output voltage setting potentiometer. Depending on the particular design, this too can result in a brief spike of maximum output voltage whenever the potentiometer is adjusted. For the sake of a few extra components, it is better to be safe than sorry.

Putting it together

The two op-amps were mounted in between the three BNC sockets placed as close together as possible.

In somewhat cavalier fashion, the ICs were mounted above the ground plane, standing on leads 1, 5 and 8, and also lead 3 in the case of IC_1. These leads had been carefully bent down from the usual horizontal position on a surface mount device, the remaining leads having been bent upwards.

A 10nF 0805-packages chip capacitor was then soldered between the ground plane and each supply lead, leaning in towards the device at an angle of about 60° from the vertical. The leaded 100n capacitors – also four in total, these items of Fig. 4 being duplicated – were then also fitted, to each side of the op-amp to leave space for the chip resistors.

The chip resistors were then fitted, the feedback resistors around IC_1 and IC_2 being mounted on top of the devices, directly between the bent-up pins 2 and 6. As the body length of the 100Ω input resistor to IC_1 was not sufficient to reach the shortened spill of the BNC centre contact at Port A, the gap was bridged by a few millimetres of 3mm wide 0.001in copper tape. The same trick was used elsewhere, where necessary.

If you don't have any copper tape to hand, a little can always be stripped from an odd scrap of copper-clad. The application of heat from a soldering iron bit will enable the copper to be peeled from the board. This is possible with GRP and even easier with SRBP.

Testing the prototype

The finished prototype was fired up and tested, using the equipment briefly described later. Performance up to several hundred megahertz was very encouraging, but it was obviisly sensible to try and wring the last ounce of performance from the circuit.

Reproduced from the *AD8009* data sheet, **Fig. 5a)** shows how a useful increase in bandwidth can be achieved by the addition of different small amounts of capacitance to ground from the op-amp's inverting input, at the expense of some peaking at the top end of the frequency range.

Figure **5b)** shows the effect of those same values of capacitance on the pulse response. In Fig. 4, the op-amps are used at a gain in excess or +10dB, so the same degree of bandwidth extension cannot be expected for sensible values of capacitance at the op-amp's inverting input.

After some experimentation, in the case of IC_1 a value of 1.8pF was selected. In the case of IC_2, the value of capacitance was adjusted for best device directivity. This involved terminating port B with a 50Ω termination and tweaking the capacitance to give the greatest attenuation of the residual signal at port C in the 300 to 500MHz region.

As the required value was around 1pF, lower than the minimum capacitance of the smallest trimmers I had in stock, it was realised as two short lengths of 30SWG enamelled copper wire twisted together. The length was trimmed back for optimum directivity as described above, leaving just over 1cm of twisted wire.

The transmission path from port A to B and that from port B to C both showed a smooth roll off above 500MHz, with no sign of peaking.

Isolator performance evaluation

After using the equipment described above to optimise the isolator's performance, some photographs of the screen display were taken for the record. The upper trace of **Fig. 7** shows the output of the tracking generator, connected via two 10dB pads and two coaxial cables connected to the input of the spectrum analyser. These cables are joined by a BNC back-to-back female adapter.

The sweep covers 0 - 500MHz and the vertical deflection factor is 10dB per division. The back-to-back BNC connector was then replaced by the isolator, input to port B, output from port C.

A second exposure on the same shot captured the frequency response of the isolator, Fig. 7, lower trace. It can be seen that the insertion loss of the isolator is negligible up to 300MHz, and only about 3dB at 500MHz. The response from port A to port B is just a little worse, as this path could not use the frequency compensation provided by the 3.9pF capacitor in the output pad at port C.

Figure 8 shows the reverse isolation from port B (as input) to port A (lower trace; with the input, upper trace, for comparison). This can be seen to be mostly 45dB or greater, and better than 40dB right up to 500MHz.

Given an ideal op-amp with infinite gain even at 500MHz, the negative feedback would ensure an effectively zero output impedance. Then, IC_1 would be able to swallow any current injected into its output from port B with none passing via R_1 to port A.

At lower frequencies this is exactly what happens, the lower trace reflecting in part the limitations of the instrumentation. The fixed 2.05GHz oscillator Tr_1 in Fig. 6 is of course running at the analyser's first intermediate frequency. So any leakage from Tr_1 back into the analyser's first local-oscillator output, and from there into the first intermediate

Equipment used for the testing

With such a wideband device, any sensible evaluation of its performance required some form of sweep equipment.

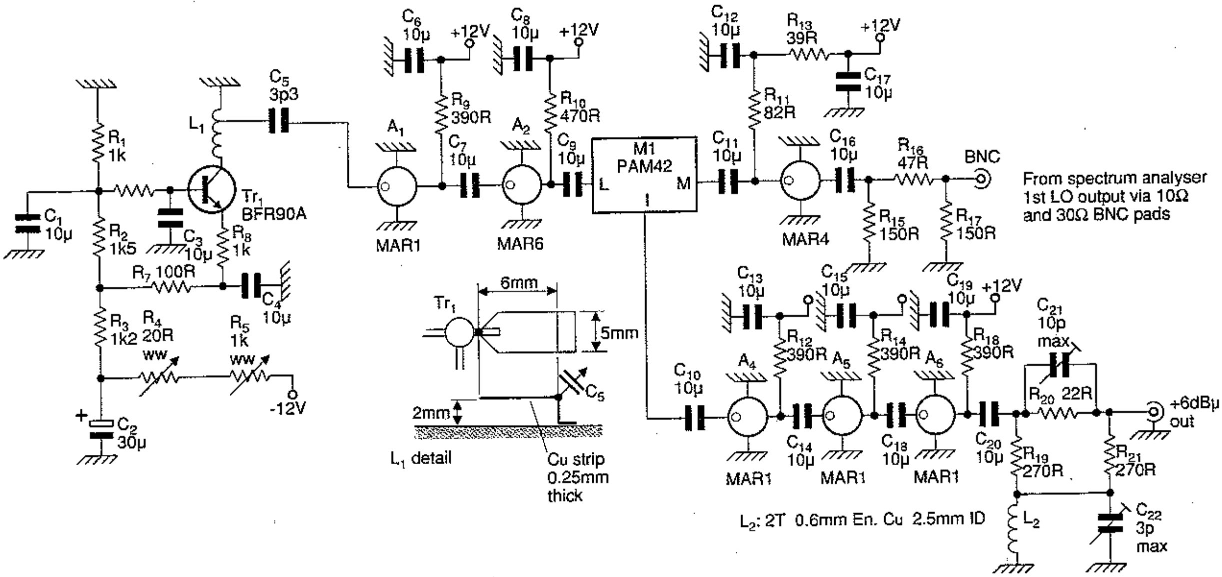
For general rf measurements, I have a Hewlett-Packard 0.1 to 1500MHz spectrum analyser type *8558B*, which is a plug-in unit fitted in a *182T* large screen display mainframe. I bought the mainframe and plug-in as a complete instrument, tested and guaranteed, from one of the dealers in this type of second hand equipment who advertises regularly in this magazine. Being an older instrument, long out of production, it is available at a very modest price, considering its performance.

Unfortunately, this instrument does not include a built-in tracking generator. Those only came in with the introduction of a later generation of spectrum analyser. But it does make a sample of the 2.05 to 3.55GHz first local oscillator available at the front panel.

Some time ago I published a circuit for an add-on for such an instrument.[2] It accepts an attenuated version of the spectrum analyser's first local oscillator output and mixes it with an internally generated continuous wave centred on 2.05GHz.

The output, as the spectrum analyser's first local oscillator sweeps from 2.05 to 3.55GHz, is a tracking output covering the analyser's 0 to 1500MHz input range.

Fig. 6. Circuit of an applique box for an HP 8558B spectrum analyser, providing a 0 - 1500MHz tracking generator output. (Reproduced courtesy **Electronic Product Design,** *July 1994, page 17.*



frequency stage, is by definition always on tune. Indeed, the purpose of $R_{4,5}$ is precisely to permit tuning of the fixed oscillator – which is not in any way frequency stabilised – to the analyser's first intermediate frequency.

The purpose of the external 13dB pad between the analyser's first local oscillator output and the applique box, and the latter's internal pad $R_{15\text{-}17}$ is to minimise this back-leakage. Despite these precautions, even with the input to the spectrum analyser closed in a 50Ω termination, the residual trace due to leakage is only a few decibels below that shown in **Fig. 8**.

Testing the isolator's directivity

My main use for the isolator is as a means of testing the vswr of various items of rf kit, such as antennas, attenuators, the input and output impedances of amplifiers, etc. To determine just how useful it was in this role, the output at port C was recorded, relative to the input at port A, for various degrees of mismatch at port B, **Fig. 9**.

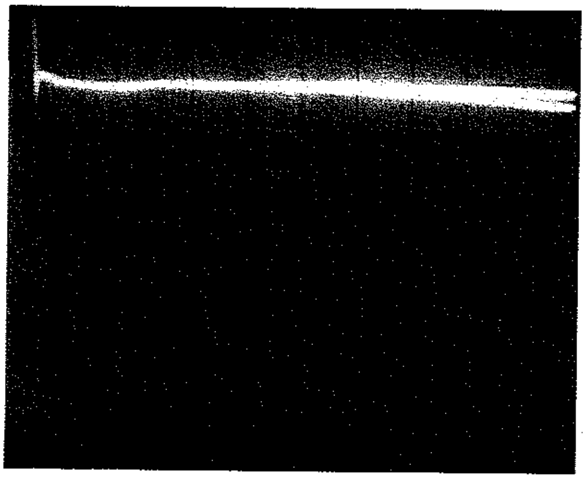


Fig. 7. Upper trace, output of the tracking generator, attenuated by 20dB. Lower trace, as upper trace, but with the signal routed via port B to port C of the isolator. Reference level –2.5dB, 10dB/division, span 0 to 500MHz, intermediate frequency bandwidth 3MHz, video filter medium.

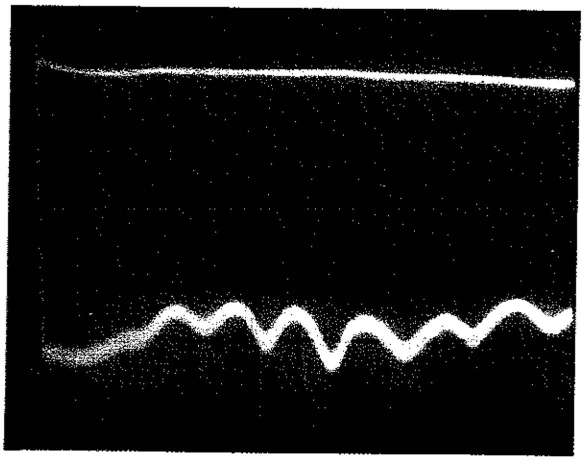


Fig. 8. Upper trace as Fig. 7, for reference. Lower trace, output from port A of the isolator with the input applied to port B. Spectrum analyser settings as for Figure 7 except video filter at max.

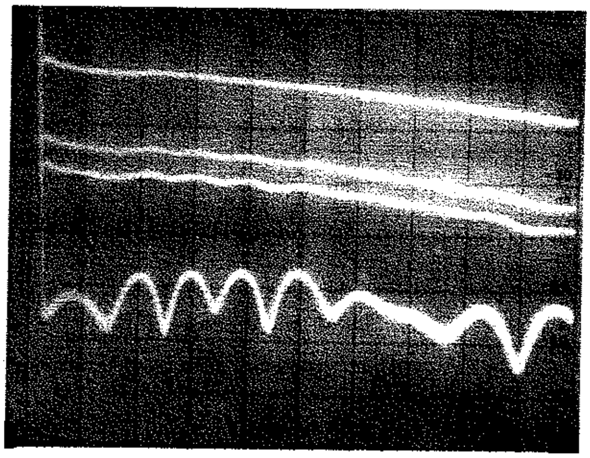


Fig. 9. Traces showing the signal at port C for various degrees of intentional mismatch at port B: with (top to bottom) return loss of 0, 14, 20 and 74dB. Signal applied to port A as in Fig. 7, upper trace. Spectrum analyser settings as for Fig. 8.

The top trace is the output level with an open circuit at port B. Comparing it with the upper trace in Fig. 7, it is about 7dB down at 500MHz, this being the sum of the insertion loss from port A to port B, plus the insertion loss from port B to port C – already noted in Fig. 7 as around 3dB.

The three lower traces in Fig. 9 are with a 75Ω termination at port B providing a 14dB return loss, a 50Ω 10dB pad open at the far end providing a 20dB return loss, and three 50Ω 10dB pads terminated in 75Ω. The latter works out as a theoretical 74dB return loss, or close to 50Ω, and the resolution of the system as measured is apparently limited to around 40dB. A return loss of 40dB corresponds to a reflection coefficient of 1%. Now,

$$\rho = \frac{Z_t - Z_o}{Z_t + Z_o}$$

where Z_t is the actual value of the termination and Z_o is the characteristic impedance viz. 50Ω. So ρ=1% corresponds to a Z_t of 51Ω. The dc resistance looking into the string of three 10dB pads plus the 75Ω termination was measured at dc as 50.6Ω.

Clearly, then, assuming this is still the case at 500MHz, much of the residual signal in the bottom trace in Fig. 9 can be assumed to be due to the error in the characteristic impedance of the pads. These were normal commercial quality, as opposed to measurement laboratory standard.

For the rest, it is down to the limited directivity of the isolator. To maximise this, the chip resistors were all selected to be well within 1%, from the supply of 5% chips to hand. I had originally hoped to be able to select 326.3Ω resistors from the 313.5Ω to 346.5Ω spread of 330Ω 5% resistors. But most were in fact within 1%, hence the need for a parallel 15kΩ to secure the right value.

But the interesting – and indeed vital – point is that the directivity of the system does not depend on the flatness of the frequency response. The fact that the three upper curves in Fig. 9 are so nearly identical and parallel, indicates that the isolator is useful for vswr measurements right up to 500MHz, and perhaps a bit beyond. This is because the directivity depends upon two things.

Firstly, that the balance of the bridge of resistors at the input of IC_2 in Fig. 6 remains constant with frequency. Secondly, that the common mode rejection of the opamp remains high right up to 500MHz. And in view of the excellent results obtained, this certainly seems to be the case.

Using the isolator

The spectrum analyser, together with its hand-made tracking generator was very useful for demonstrating the isolator's performance over the whole band up to 500MHz in one sweep. But the arrangement has its limitations.

Apart from the back-leakage from the 2.05GHz oscillator, already mentioned, there are two other limitations. Firstly, as the 0 to 500MHz sweep proceeds, the frequency of the 2.05GHz oscillator tends to be affected slightly, so that it is necessary to use a wider than usual intermediate-frequency bandwidth in the analyser. Secondly, to maintain a sensibly flat output level, the output is taken from an overdriven string of amplifiers, with resulting high harmonic content. This is normally of no consequence, since the analyser is selective and is by definition, tuned only to the fundamental. But problems can arise with spurious responses due to the presence of the harmonics.

Where a more modest frequency range up to 200MHz suffices, the sweeper described in reference 3 can be used, in conjunction with a broadband detector – perhaps preceded by a broadband amplifier – connected to port C. A successive-detection logarithmic amplifier makes a very convenient tector, and types covering frequencies up to 500MHz are mentioned in reference 4.

For many applications, a swept measurement is not essential, for example when adjusting a transmitting antenna for best vswr at a certain frequency. In this case, any convenient signal generator can be used. At the higher frequencies however, it is best to keep the input to port A to not more than 0dBm.

A receiver can be pressed into service as the detector at port C. Many receivers, for example scanners, include an RSSI facility. In many cases, these make surprisingly accurate logarithmic level meters.

Measuring the level at port C relative to that at port A gives the return loss, and hence the vswr, of the device under test connected to port B. Tuning/adjusting it for maximum return loss will provide a device under test with an optimum vswr. Return loss measurements can be cross-checked at any time by substituting an attenuator(s) and/or 75Ω termination for the device under test, as described earlier.

Could it sing?

Finally, an interesting point about this active circuit. No problem was experienced at any stage with instability. But what about the circulator of Fig. 2? Here, any reflected power at port C circulates back around to port A.

What happens if all three ports are left open circuit? Given that tolerance variations on the resistors could result in a low-frequency gain marginally in excess of unity in each stage, could the circuit 'sing around' and lock up with the op-amp outputs stuck at the rail?

In fact the answer is no, because as Fig. 3 shows, when a port is open circuit, the output of the following op-amp is of the opposite polarity. In this way, the voltage passed on to the next stage is of the opposite polarity to the reflected voltage at the stage's input.

Three inverters in a ring are dc stable, and at frequencies where each contributes 60° phase shift or more, the loop gain is already well below 0dB. Of course, if all three ports are shorted, each stage passes on a voltage – possibly marginally greater – of the same polarity and lock-up is a possibility. But I can't think of any circumstances where one might want to try and use a circulator with all its ports short circuited! ■

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