

Wideband Component Design

Directional Couplers

In some systems it is necessary to have a continuous wideband directional coupler to provide a separate output that informs the user of how much power is in the main line and in which direction it is going.

The critical parameters for a directional coupler are:

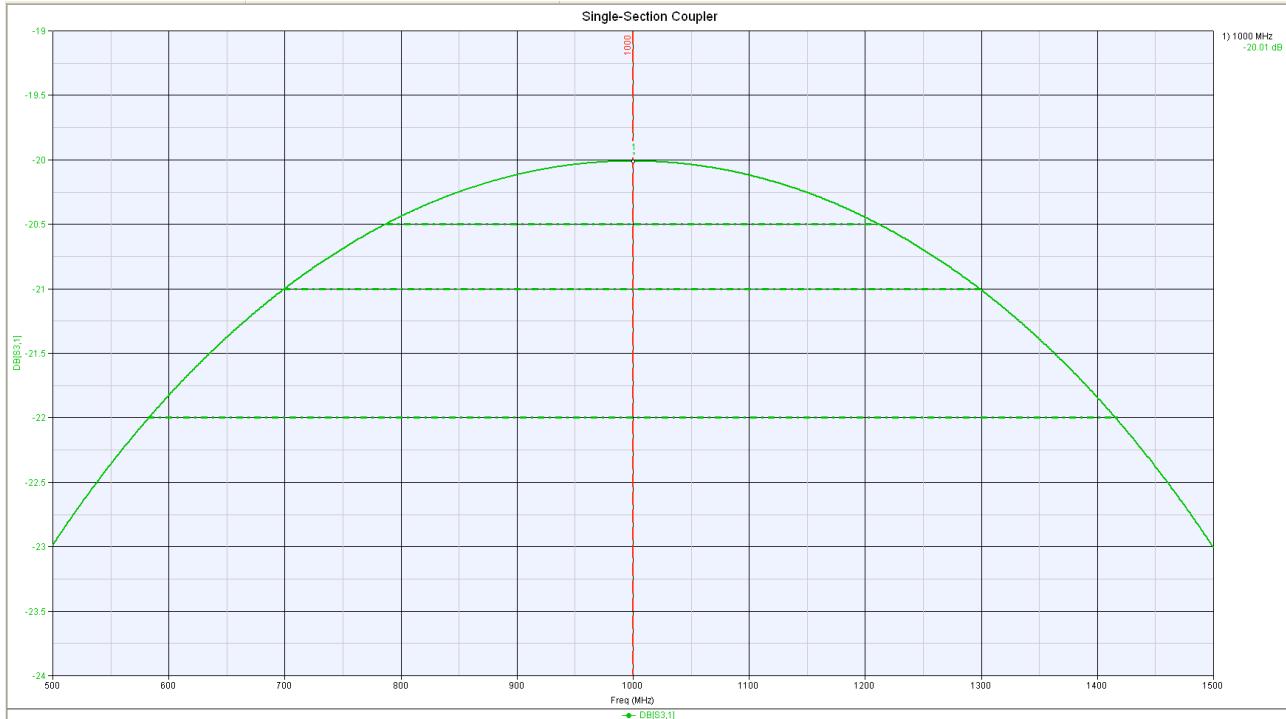
Insertion Loss	Through Line loss is always required to be low
Coupling Value	to provide a sensible level of power to the detector
Coupling Ripple	to provide the required level of accuracy
Directivity	to separate forward and reverse power
VSWR	Through Line match to be almost perfect
	Coupled Line match needs to be reasonable
Power Rating	a high input power dictates a larger physical coupler.

A simple directional coupler is just two transmission lines close together such that the secondary line can absorb energy from the field created around the primary. The resulting structure can have many properties, some of which are desirable and others which are not.

The Through Line, or Main Line, needs to be designed for the best possible match and must be capable of handling whatever the maximum input power level is specified to be.

The quality of match for the Coupled Line will affect the Directivity of the finished coupler however, some types of coupler will show a greater sensitivity to this than others. For example, if you intend to use both ends of a single coupled line to provide Forward and Reverse coupled output, then the match of this line and also the match of the external components are absolutely critical to Directivity. However, if the coupled line will have a termination at one end, then this may be tuned to optimise directivity. It is perfectly feasible to create a dual directional coupler using two separate coupled lines each of which is terminated at one end.

Standard Single Section Directional Coupler:



This is a standard design curve for a directional coupler centred on 1GHz:

0.5dB Ripple across 788MHz to 1,212MHz 1.53:1 bandwidth

1.0dB Ripple across 700MHz to 1,300MHz 1.85:1 bandwidth

2.0dB Ripple across 583MHz to 1,417MHz 2.43:1 bandwidth

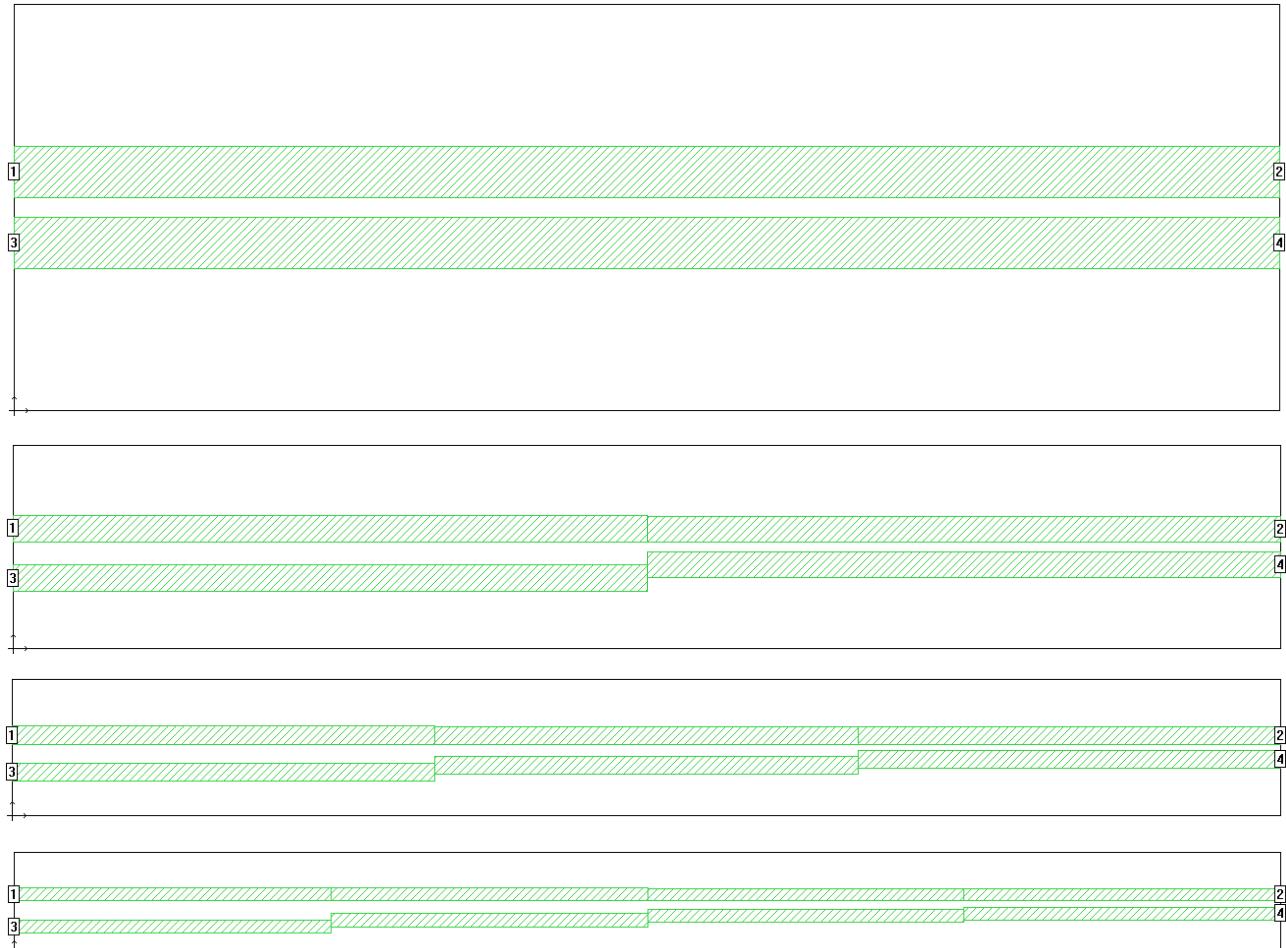
3.0dB Ripple across 500MHz to 1,500MHz 3.00:1 bandwidth

This implies that a typical operational system within a single specified operating band can usually use a simple, relatively small and low cost, single section directional coupler to provide a coupled output level with good ripple.

The problem arises when the same coupler must work on a range of systems, or when a wideband application is specified, or when test instrumentation is required to work across many different operating bands.

Multi-Section Couplers:

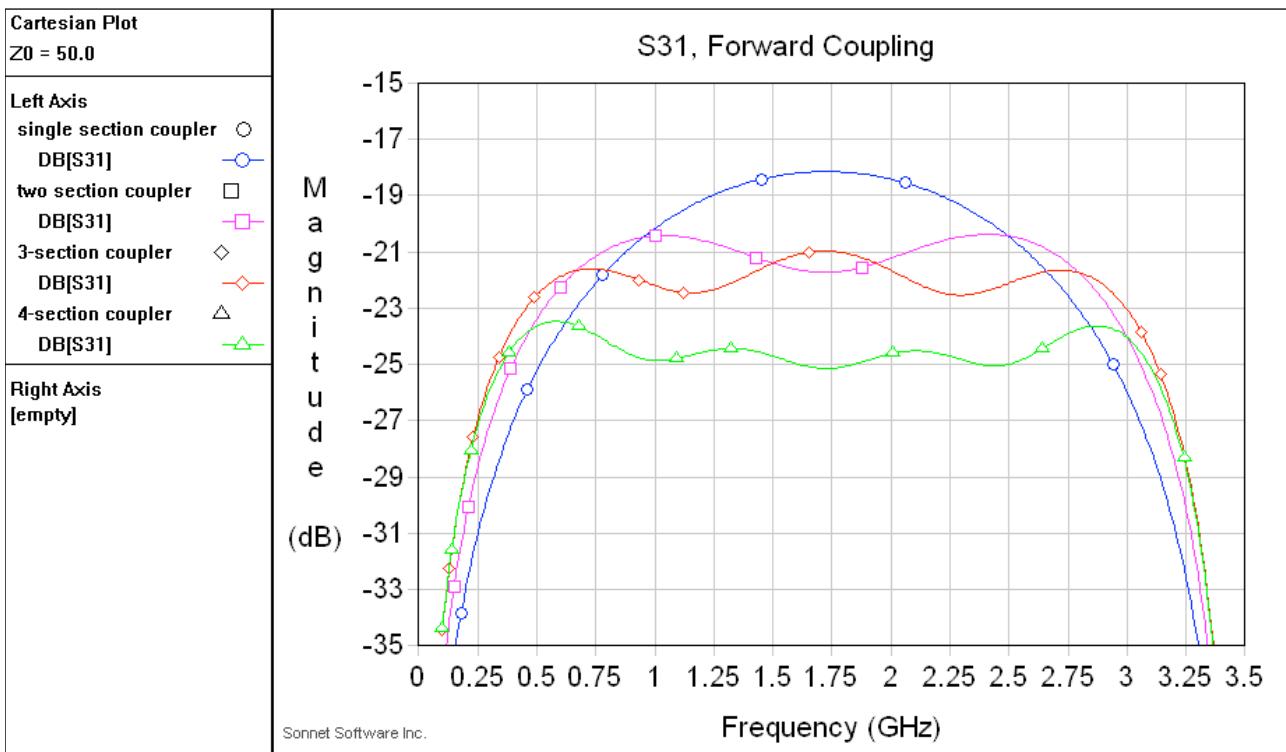
One method of achieving a wideband directional coupler is by the use of re-combining sections.



Each section in all 3 pictures above is the same length, the scale of each picture changes to fit the page.

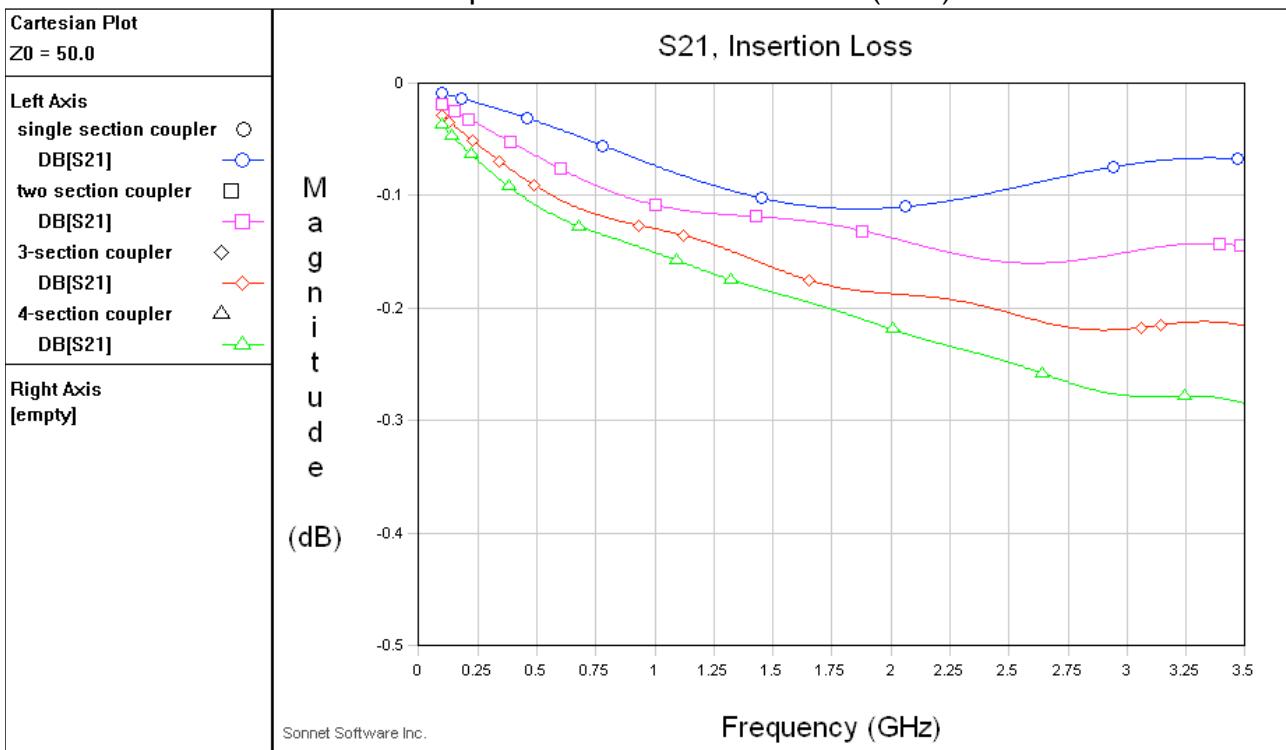
The closest coupling section determines the basic coupling value, while the more loosely coupled sections re-combine the coupled power to provide a wideband, rippled, response.

It must be remembered that a single section coupler has fixed 90° phase relationship between S21 and S31. If this is important to your system design then you must use identical re-combining sections either end of the closest coupling section. The method shown here uses asymmetric re-combining which provides amplitude levelling, but destroys the phase relationship



$\pm 1\text{dB}$ ripple for

- 1-section coupler from 1.05GHz to 2.4GHz (2.3:1)
- 2-section coupler from 0.60GHz to 2.85GHz (4.75:1)
- 3-section coupler from 0.45GHz to 3.0GHz (6.66:1)
- 4-section coupler from 0.33GHz to 3.1GHz (9.4:1)



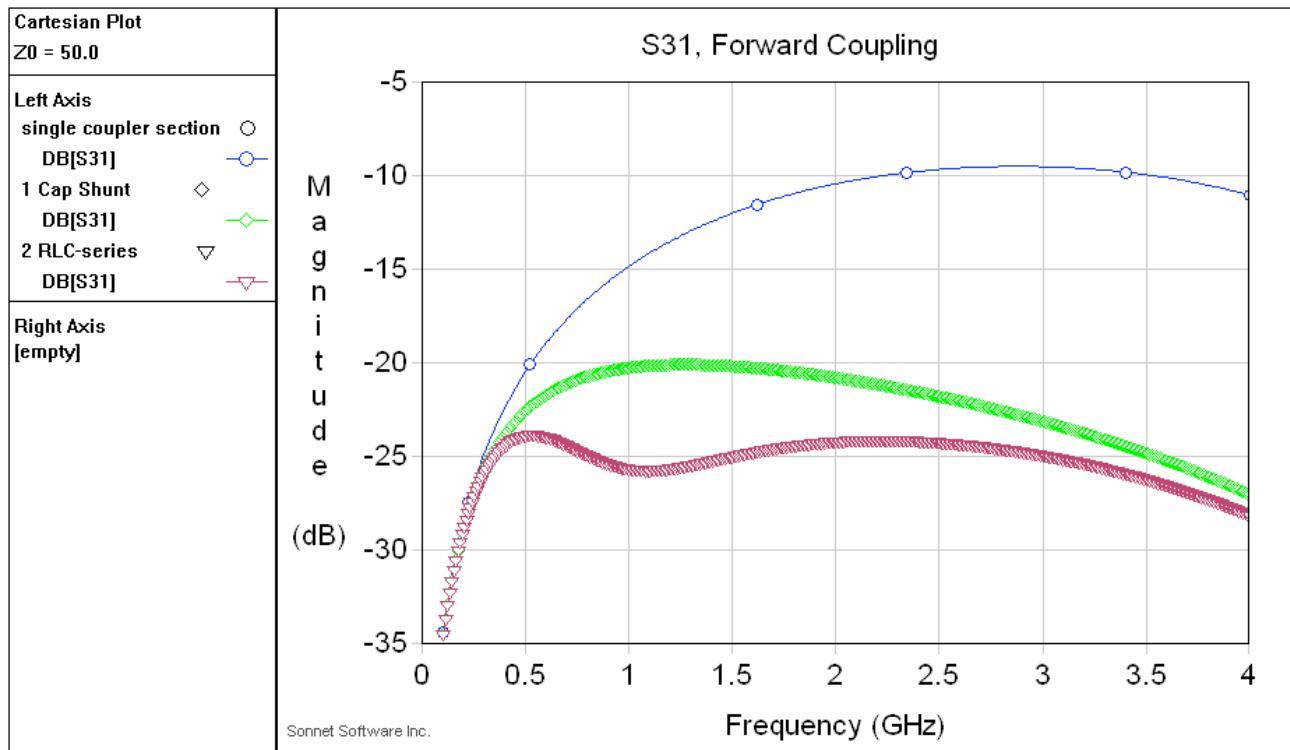
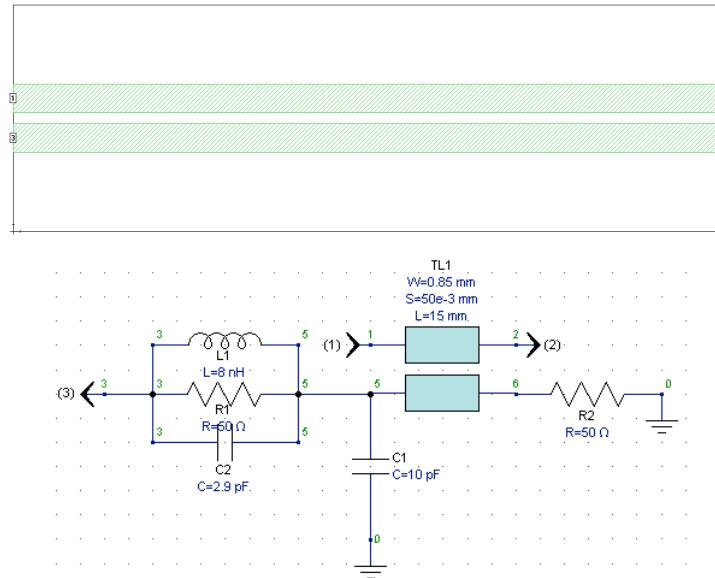
One key factor of the multi-section wideband coupler is the very low insertion loss that is maintained for the Through Line as no power is wasted, it is all re-combined.

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Equalised Couplers:

These are generally designed with a single section coupler centred at, or close to, the highest frequency in the required operating band in order to provide a monotonic curve suitable for amplitude equalization.

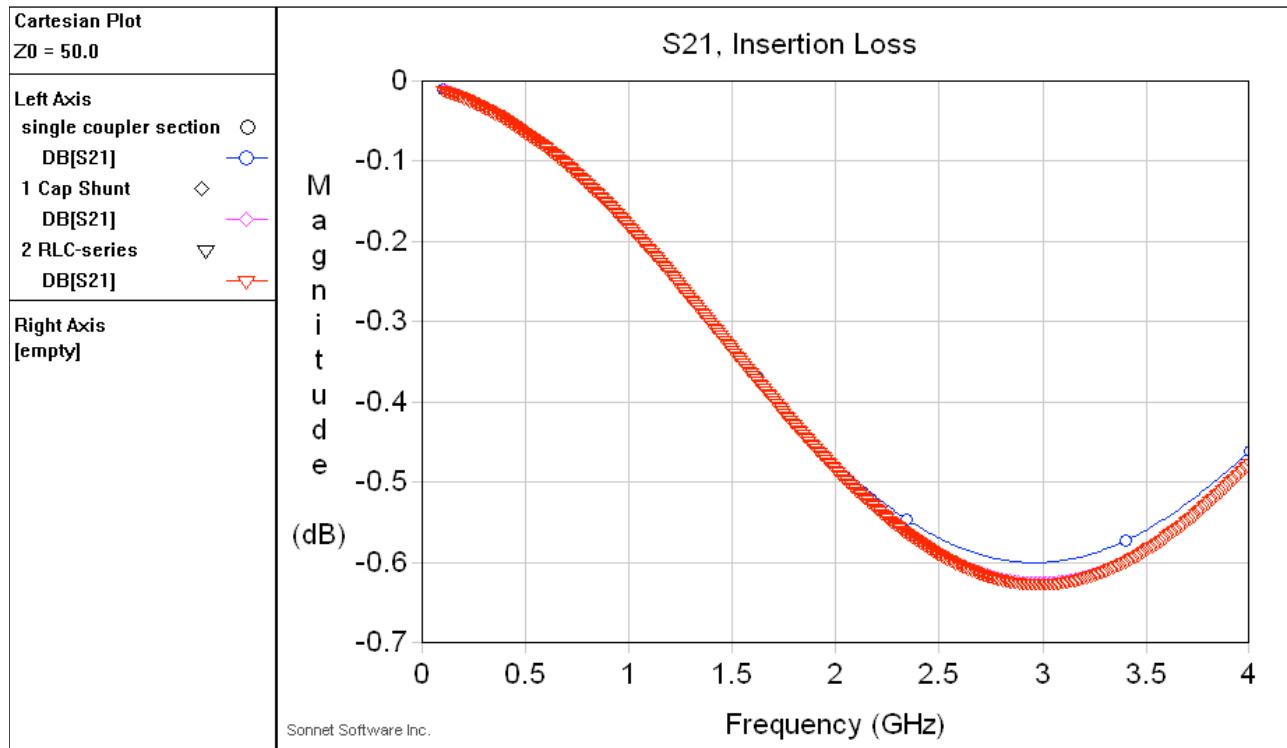


The blue line is the un-equalised coupled output.

The green line is equalisation just from the shunt capacitor.

The red equalised output level is $25\text{dB} \pm 1\text{dB}$ from 0.3GHz to 3.2GHz, however there are two main issues that need to looked at more closely.

These first issue can be seen by realising that the blue, raw coupling, line increases to almost 9dB at 3GHz, which will couple 12% of the incident power from the Through Line into the Coupled Line



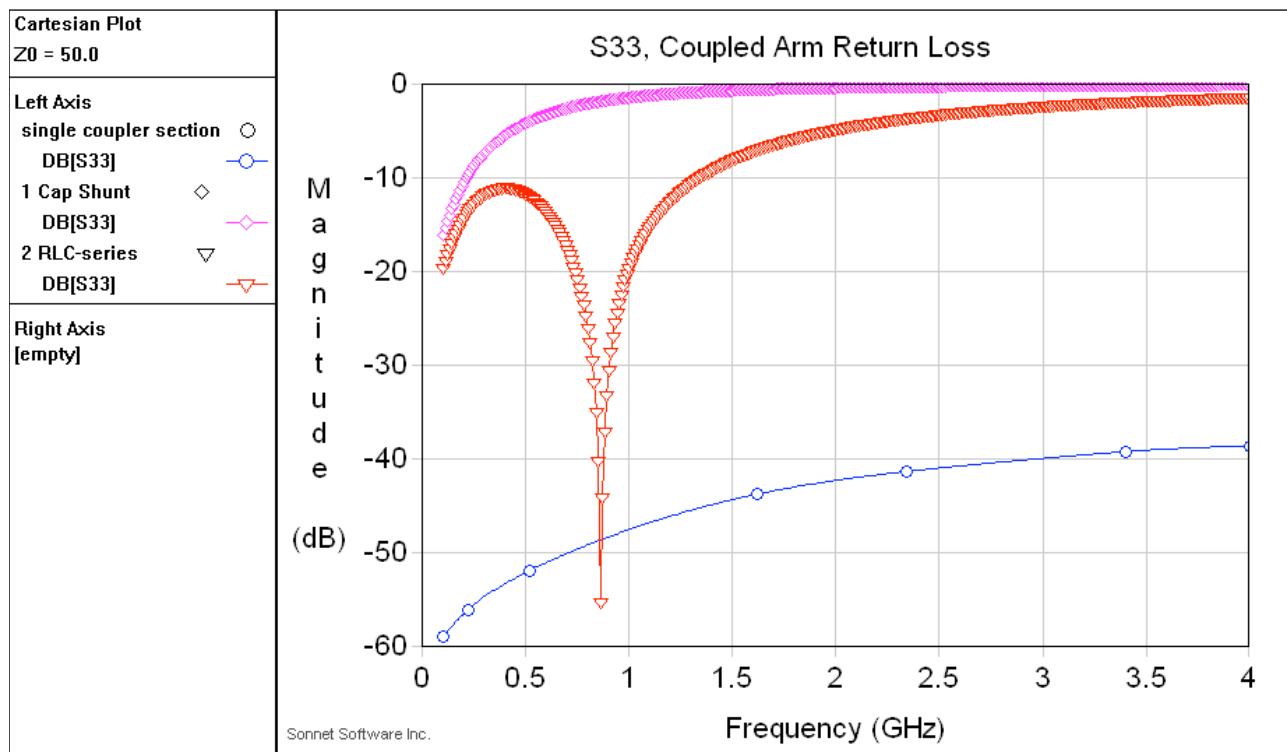
This shows that even though the coupled section is very short and actually very low loss, the output power of the Through Line sees a loss of 0.6dB

If the input power is 1KW, then the power that has to be dumped into the 50ohm termination is 129Watts. This power was probably very expensive to generate in the first place and this amount of heat is very expensive to remove.

Therefore, this implies that an Equalised Coupler should only be used for much weaker coupling values such that the peak raw coupling is no more than 20dB and preferably about 30dB.

This would reduce the Equalized coupling level to 36dB or, preferably, 46dB.

The second issue can be seen if you look at the equalising circuitry and consider the effect on the Coupled Output Return Loss.



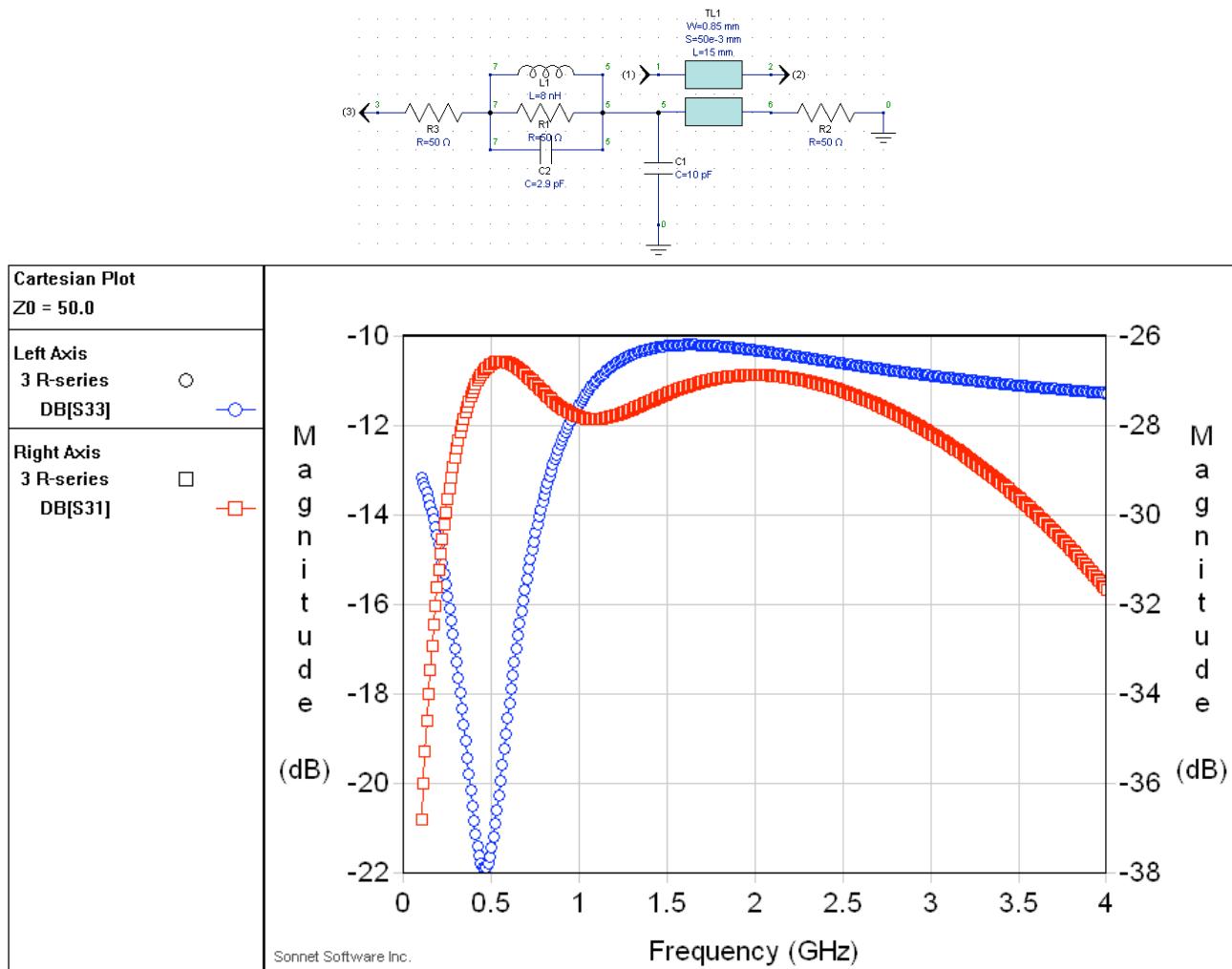
The blue line shows that native return loss of the coupled line itself.

The purple line shows the return loss with just a shunt capacitor

The red line shows the return loss with the full equalising circuit in place.

Normally you will want a reasonable return loss on the coupled port. The narrow band of good return loss is at the resonance of the LRC section on the equalised output.

If you add a resistor in series on the output as shown below



This offers a 10dB return loss worst case, which might be good enough, but also note that another 1.8dB of Coupled Output has been lost through the resistor.

It is possible to improve on the Coupled Ripple and also the Coupled Return Loss by introducing more sections into the equalising circuit, but you must remember that this will also add more loss and also make the coupler more difficult to reproduce accurately for the required ripple.

My recommendation is that an equalised coupler should really only be considered for coupled outputs of 50dB or weaker relative to the input level, with 40dB being the absolute strongest output coupling that is viable.

The Multi-Section Coupler could realise a 10dB coupling value across a 10:1 bandwidth with the S21 being just 0.2dB worse than for a single section, narrow band 10dB coupler.

Directivity:

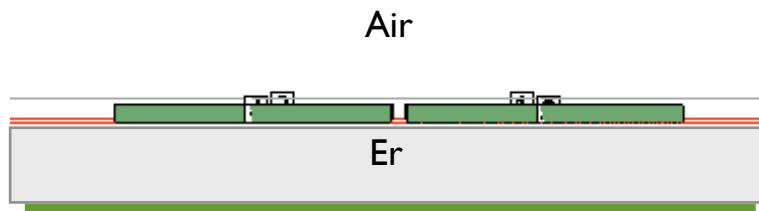
Directivity is the difference between Forward Coupling and Reverse Coupling, and is generally more a function of the build technology rather than the type of coupler discussed above.

It is actually very easy to design a coupler in theory such that it should have directivity greater than 40dB, however reality has a habit of destroying any idea that such a value is realisable.

- 1 The basic transmission line structure
- 2 Transition from the coupler to the external components, or connectors

Transmission Line Structure:

Microstrip:

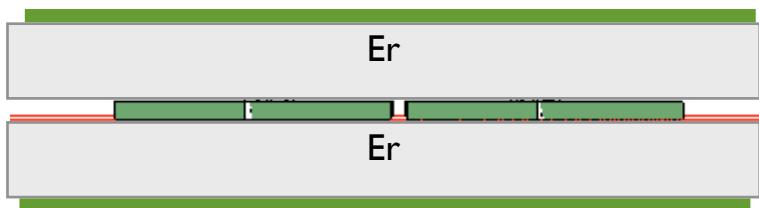


For a single microstrip conductor there is one mode of transmission, the Odd Mode. This is formed between the conductor and the Ground plane. For a typical microstrip conductor about 90% of the field is in the Dielectric substrate and only 10% is in the Air.

For coupled transmission lines there are two modes of transmission, the Odd Mode and the Even Mode. The Odd Mode is as described above. The Even Mode is between adjacent lines. This Even Mode has approximately 50% of its field below the lines in the dielectric substrate and 50% above the lines in the Air. This means that the effective Er for the Even Mode is lower than for the Odd Mode

This imbalance of the transmission modes creates a limit to the directivity that can be achieved with Microstrip lines.

Stripline:



For Stripline both the Odd & Even Modes are now 100% in the Dielectric Substrate above and below the transmission line, therefore they are in perfect balance and the limit of directivity is significantly improved.

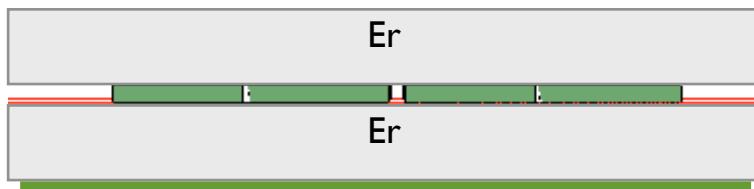
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However, there is an issue if you look closely at the join between the Top and Bottom substrates. If the Copper is Half-Ounce then the conductors are $17.5\mu\text{m}$ thick while the substrate is typically $750\mu\text{m}$ thick. The metal thickness might not seem significant relative to the substrates, but this is also the region with the strongest fields.

In practice there are two common ways of making such Stripline; one is to simply press the top layer down by screwing on the lid of the box, the other is to bond the layers together using a melttable bond film in the middle of the assembly. The first of these two methods will leave pockets of air in the centre which will vary according to the pressure from the lid. The second method is potentially much more reliable so long as you are careful to match the bond film Er to that of the substrate.

Buried Microstrip:



There are two main potential reasons for not wanting to use Stripline; these are the reduced power handling from the narrower transmission lines and the potential cost of making the Stripline part when everything else is Microstrip.

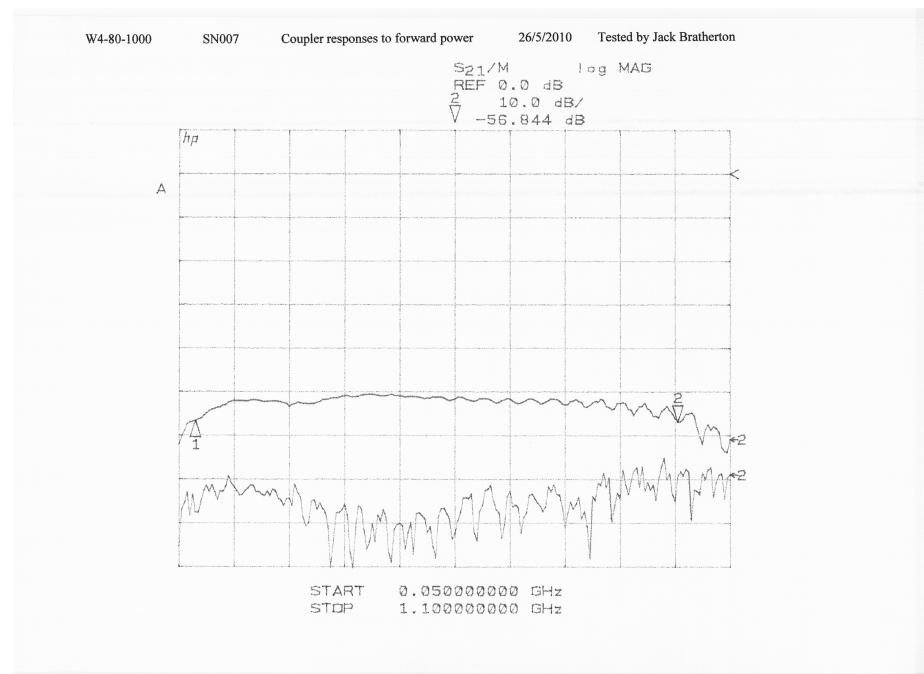
The disadvantage of Microstrip is the imbalance of the Odd and Even Modes due to the effect of the Air.

A compromise solution is offered by Buried Microstrip where the top layer of dielectric is exactly the same as the bottom layer, but there is no ground plane on top. This means that over 99% of the energy of both Odd and Even Modes are transmitted within the dielectric. Therefore, the potential directivity is almost as good as for Stripline, while the power handling is almost as good as for Microstrip.

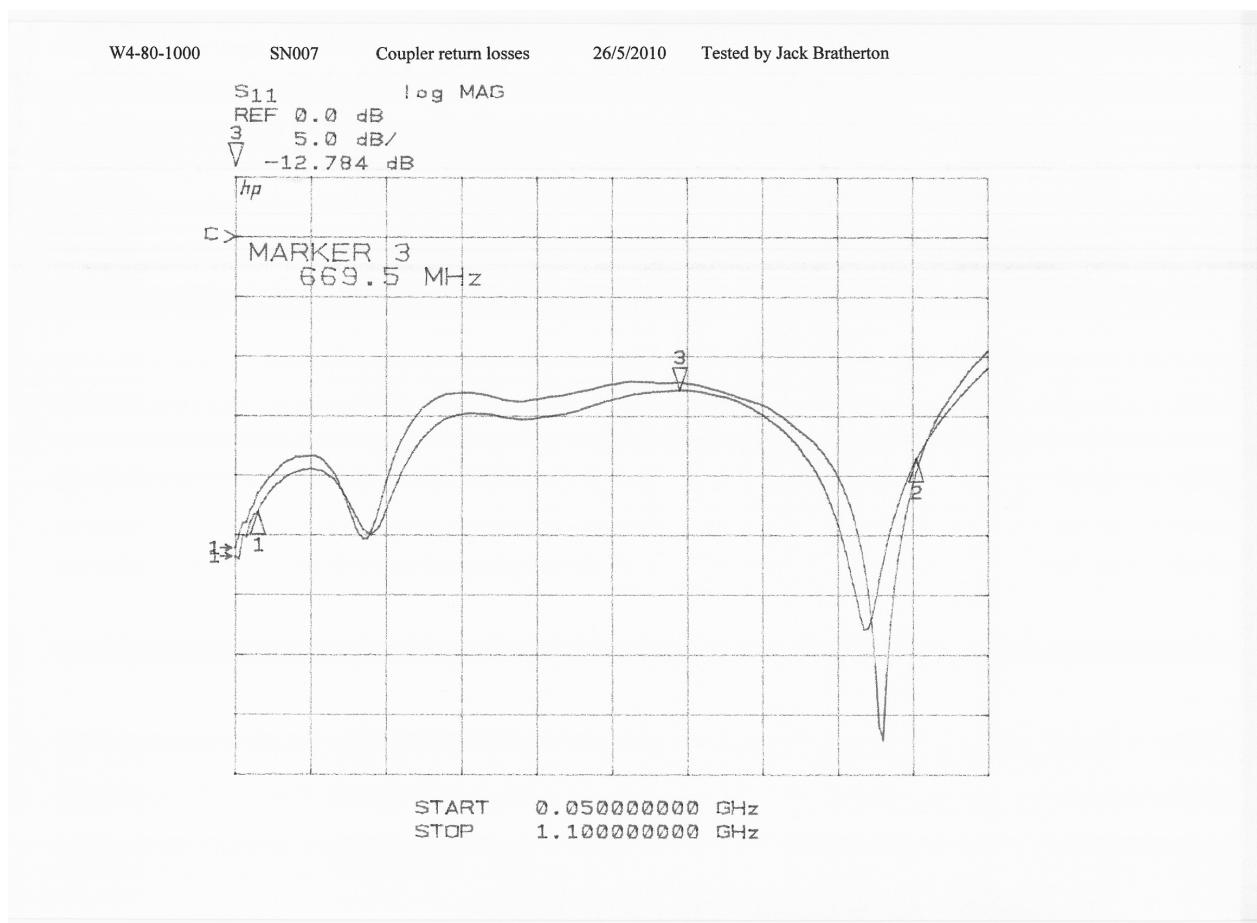
This photograph is of a Dual Directional Coupler for 80MHz to 1GHz



The through line of this coupler forms part of the matching network for a 4-way 2KW power combiner covering 80MHz to 1GHz



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These measured plots show the performance of a typical unit with better than 12dB return loss for the output of the coupler equaliser circuits and directivity of better than 20dB across most of the band, reducing to 15dB at the highest frequency.

Anisotropic Dielectric Substrates:

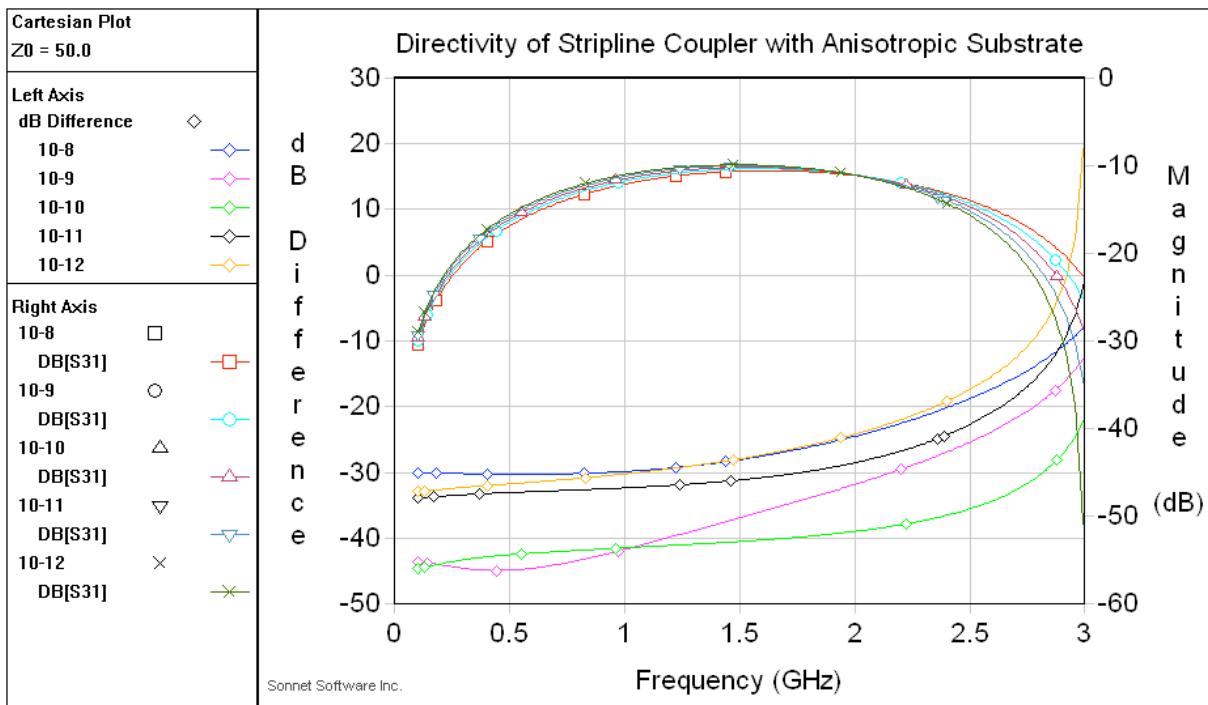
There is another problem that has been overlooked by most people due the lack of information and the fact that most board manufacturers have simply ignored reality. If you look at any data sheet from any manufacturer for almost any dielectric material you will see a single number for ϵ_r , or possibly different ϵ_r values at a few different frequencies.

What no one will tell you is that the ϵ_r -xy is different from ϵ_r -z. The quoted value is actually the measured ϵ_r -z and even this is usually wrong.

The reason for the anisotropy is the structure of the material. The reason for the lack of information is that ϵ_r -z is easy to measure, while ϵ_r -xy is significantly more difficult.

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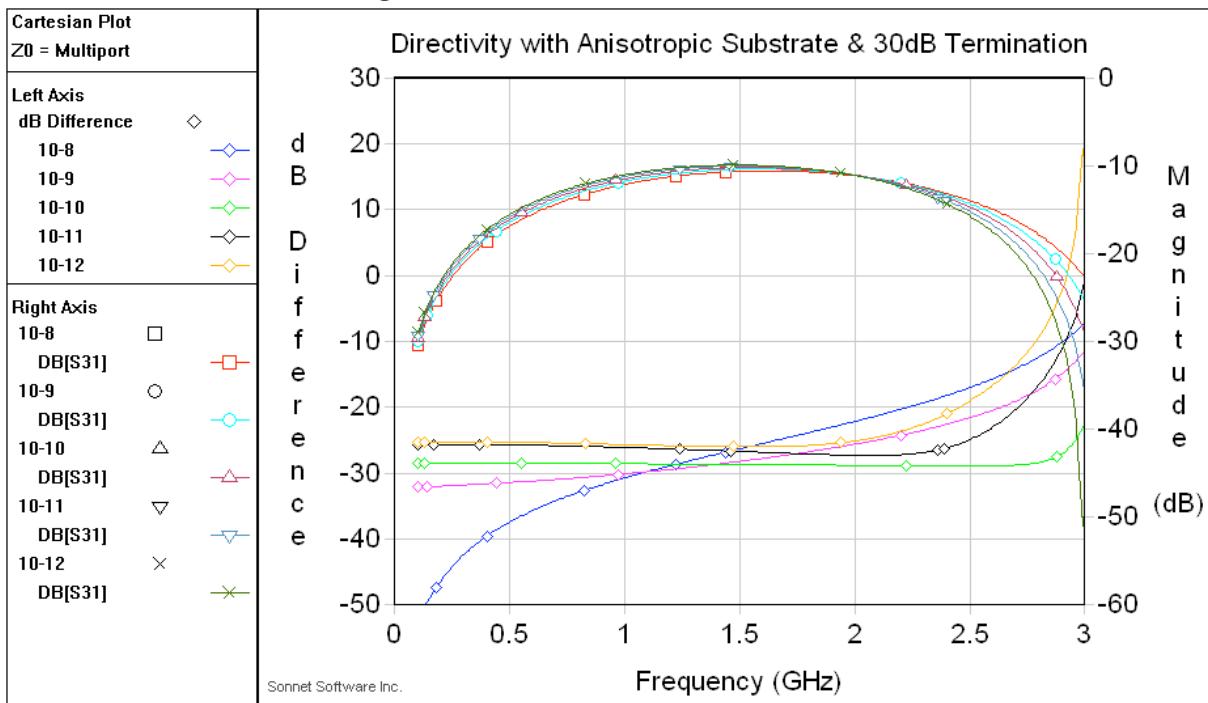
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The coupling curves hardly change below 2.5GHz with the change in the Er-xy, however the directivity changes significantly.

The green line shows the directivity for a perfectly Isotropic material at 40dB

The following plot shows the effect on the identical couplers shown above of the Port 4 termination having a 30dB return loss:



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