High Level Miniaturization for Quadrature Hybrid Directional Coupler

Directional couplers are four-port passive circuits comprising a pair of inputs and a pair of outputs [1]. Ideal hybrid couplers are perfectly matched at all ports, both input ports are mutually isolated and output ports are mutually isolated. A common application of a hybrid coupler is for splitting an input signal into two output signals. A quadrature hybrid provides a 90 relative phase difference between the output signals for a signal incident on either input port. Regarding the signal split ratio of a hybrid, the most frequent applications demand equal splitting of the input signal between two identical circuits so the equal power split hybrid is the most common. The operation of the hybrids can be reversed, i.e. hybrids can be used for combining signals. Traditional quadrilateral hybrid [2] is shown in Fig. 1.

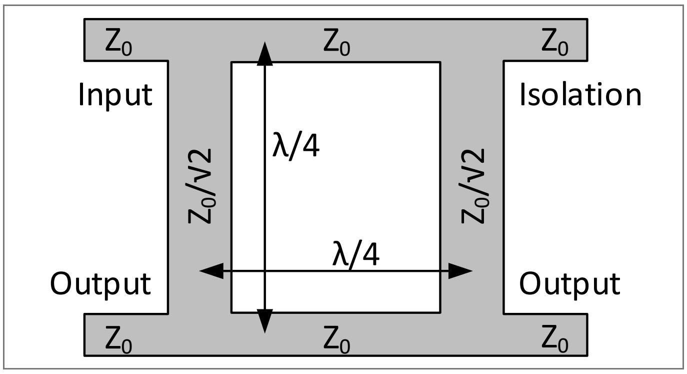

Figure 1. Traditional quadrilateral hybrid directional coupler.

This type of hybrid directional couplers is easily realized in microstrip or stripline technology. Simple design and inexpensive manufacturing make this coupler the most frequently used part in many complex microwave and RF systems. It can be used as building block for signal samplers, amplifiers, balanced and IQ mixers, RF modulation and demodulation, etc.

As a rule of thumb, the dimensions of a traditional quadrilateral hybrid (branch-line) are determined from a quarter-wave length at the operating frequency. The central part of the coupler does not contain any conductors and represents an idle area of a printed board. At low frequencies, the idle area is very large which makes the coupler utilization difficult in modern miniaturized circuits.

In this application note, a technique for miniaturization of quadrilateral hybrid operating at a low microwave frequency is demonstrated. Artificial quarter-wavelength lines are utilized to reduce the coupler dimensions [3].

Traditional Coupler

As a point of reference, a traditional branch-line directional coupler, operating at a central frequency of 1 GHz, will be designed and later compared to the miniaturized one.

Following the procedure from [2], the model of microstrip branch-line coupler is created in WIPL-D Pro CAD tool, as shown in Fig. 2. The microstrip substrate was 1 mm thick FR-4, with 0.017 mm metallization thickness. The size of the coupler is approximately 42 mm by 42 mm.

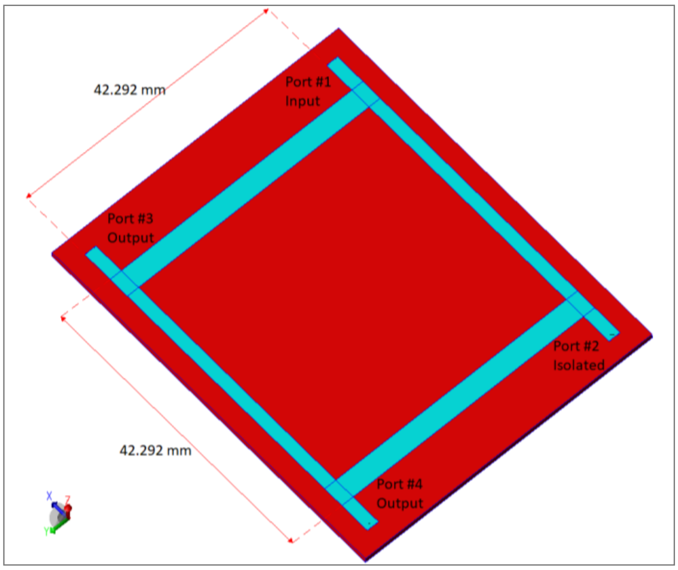

Figure 2. Traditional design of quadrilateral (branch line) hybrid directional coupler (microstrip).

Realistic model, with metal losses included, is simulated in the frequency range from 0.7 to 1.3 GHz. For an ideal hybrid, the power from the input port is equally divided to the outputs (-3 dB), with 90 degrees phase difference between the output signals, and no signal present at the isolated port. Fig. 3 shows the S parameters of the presented design at the same graph.

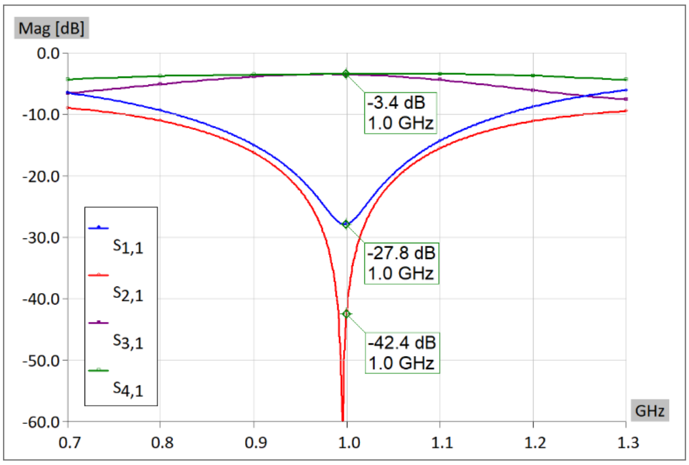

Figure 3. Magnitude of all S parameters of traditional branch-line hybrid coupler.

From the S_{11} and S_{21} curves, it can be seen that the input port is well matched (~ -27.8 dB), and that the isolation between the input ports is high (~ -42.4 dB).

Power is equally divided between the ports, S_{31} and S_{41}, but the simulated insertion loss value of ~3.4 dB is higher than the value of an ideal coupler. The increase in the insertion loss comes from the losses in the substrate and in the metal conductors.

Phase difference between output ports is presented in Fig. 4. At the operating frequency the phase difference is ~90.4 degrees.

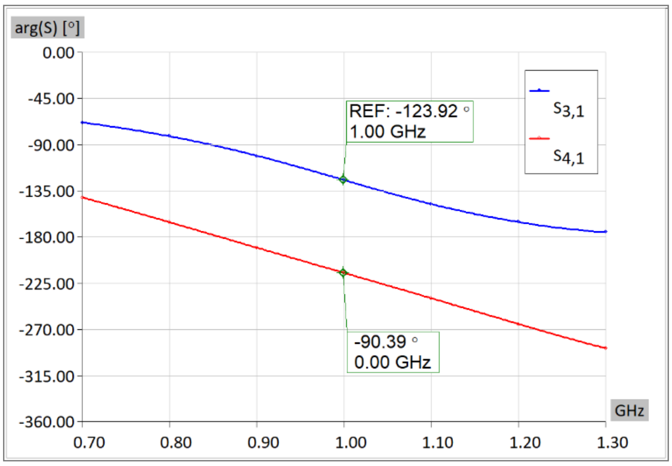

Figure 4. Phase of outputs S parameters of traditional quadrilateral hybrid directional coupler.

Owing to the WIPL-D Pro CAD software, all analysis are performed as full 3D EM simulations on inexpensive desktop machine, Intel(R) Core(TM) i7-7700 CPU @ 3.60GHz with 32 GB of RAM, equipped with NVIDIA GeForce GTX 1080 GPU Card.

Simulation details, for traditional design of quadrilateral hybrid, are presented in Table 1.

Table 1. Simulation details for traditional design of quadrilateral hybrid coupler.

Number of Unknowns	Required RAM	Simulation Time per Frequency
920	~ 6 MB	4 sec

Miniaturized Coupler

For the design of a miniature quadrilateral hybrid directional coupler, the same 1 mm thick FR-4 substrate has been used. Fig. 5 illustrates compact design of the quadrilateral hybrid directional coupler.

Artificial lines, 20.822 mm long, provide 90 degrees phase difference from one to other side of the line. Arms placed parallel to Y axis are optimized to have characteristic impedance equal to 50 Ohms, while arms placed parallel to X axis are optimized to have 35 Ohms characteristic impedance.

Both of the designs are shown side by side in Fig. 6 to illustrate the size reduction with the novel, artificial line design technique.

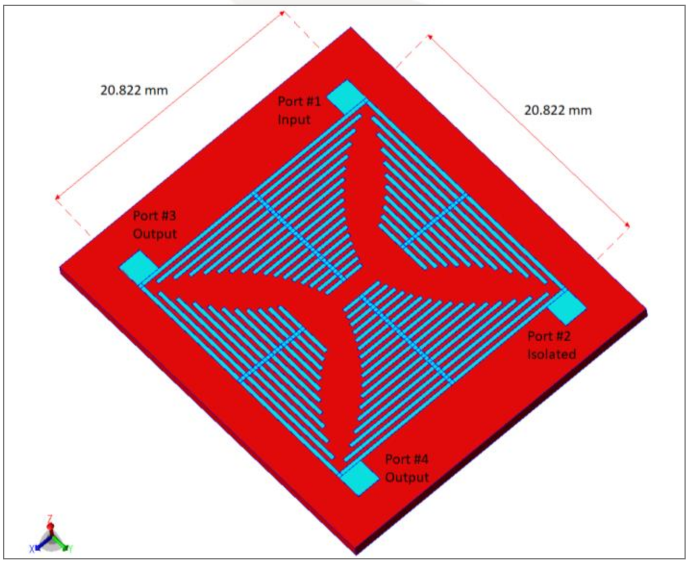

Figure 5. Compact design of quadrilateral hybrid directional coupler with artificial lines as coupler arms.

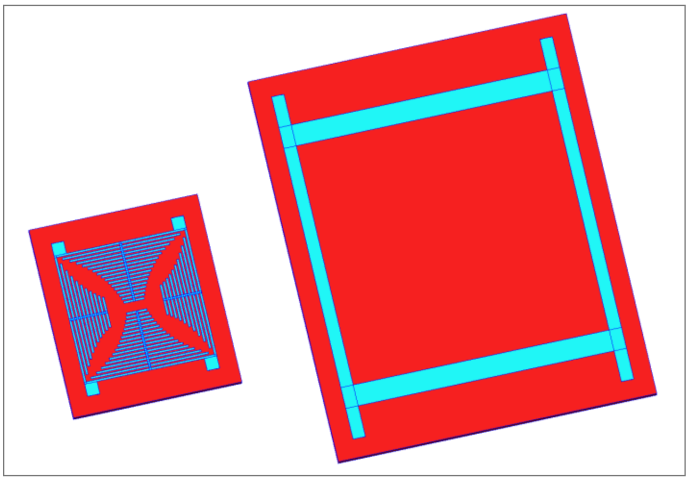

Figure 6. Comparison of compact and traditional design of quadrilateral hybrid directional coupler.

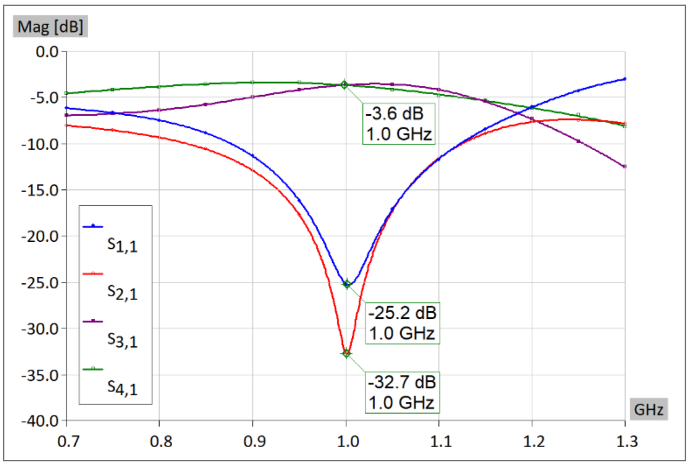

Figure 7. Magnitude of all S parameters of compact quadrilateral hybrid directional coupler.

The S_{11} and S_{21} curves, from the Fig. 7, illustrate matching at the input port (~-25.2 dB), as well as isolation between the input ports (~ -32.7 dB). Power at the output ports, S_{21} and S_{41}, are equal (~ -3.6 dB).

As presented in Fig. 8, a value of the phase difference between the output ports at the central frequency is 88.8 degrees, a bit off from the ideal value.

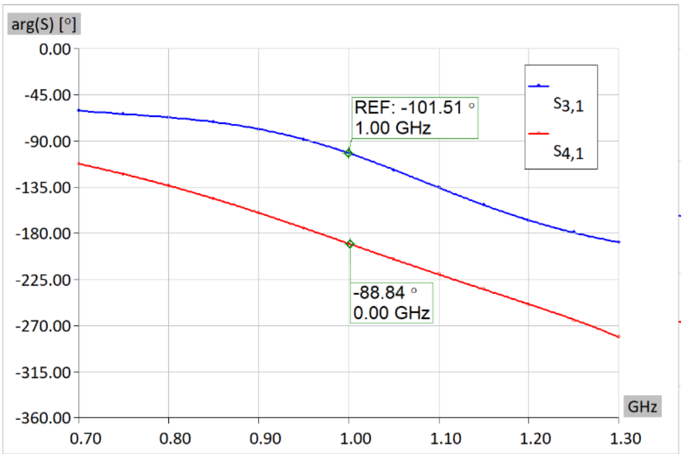

Figure 8. Phase of outputs S parameters of compact quadrilateral hybrid directional coupler.

Simulation details, for the compact design of quadrilateral hybrid directional coupler, are presented in Table 2.

Table 2. Simulation details for compact design of quadrilateral hybrid coupler.

Number of Unknowns	Required RAM	Simulation Time per Frequency
16,000	~ 2.4 GB	3.42 min

Conclusion

This application note demonstrates how compact quadrilateral (branch-line) hybrid directional couplers can be designed efficiently using the WIPL-D Pro CAD. The designs are simulated by using the traditionally fast WIPL-D full wave 3D EM simulation.

The CAD tool enables easy and fast modeling of arbitrary structures using numerous built-in primitives and manipulations. In-house code for automatic meshing into quadrilateral patches, especially optimized for WIPL-D HOBF kernel, is employed.

The WIPL-D kernel enables fast and accurate simulation of PCB structures on inexpensive machines. The traditional coupler realized in microstrip technology is simulated in just a couple of seconds per frequency. As a result of a miniaturization, its size was almost halved. However, the miniaturization requires a careful design of artificial transmission lines with numerous fine details. EM simulation of such a device is much more demanding as it requires a large number of unknowns, but the high efficiency of the simulations is preserved as it takes only a couple of minutes per frequency point. All the details significant for EM simulation such as losses, finite metallization thickness, finite size of the substrate and the ground conductor, location of the feeding point etc. are included in the model. The results presented include return loss at all of the ports, power division between the output ports, isolation between the input ports and finally the phases of the signals at the two output ports.

References

[1] https://en.wikipedia.org/wiki/Power_dividers_and_directional_couplers

[2] David M. Pozar, *Microwave Engineering*, Third Edition, John Wiley & Sons, NY, 2005.

[3] Denis A. Letavin, *Microstrip 3 dB quadrature directional coupler with a high degree of miniaturization,* 26th Telecommunication forum TELFOR 2018, Serbia, Belgrade, November 20-21, 2018 .