Product How To: Design a polar frequency discriminator

Janine Love - June 08, 2012

Polar frequency discriminators (PFD) are widely used in radar and direction-finding applications to determine the unknown frequency of incoming pulses. This article explains how to design the RF portion of a PFD, over a frequency range of 2 to 8 GHz, using Agilent’s ADS software.

At the heart of the PFD is a polar phase discriminator (PPD) or a phase correlator, which is a combination of 90 and 180 hybrids. Two amplitude limited voltages with known delay (τ) are input to the phase correlator. The PFD outputs are detected and fed to a differential amplifier. The two PFD outputs are then fed to the X-Y plates of an oscilloscope. When the input frequency is swept, a circular trace is observed on the oscilloscope. By carefully choosing the delay (τ), the trace can be made to complete one full circle (or 2N circles) over a given frequency range, f1 to f2. The unknown frequency of the pulse (ω) is directly related to angular position (φ) of the trace. Hence, by measuring the angle between I and Q channels (φ) of the detected voltages, it is possible to calculate the input (unknown) frequency ω, using the relation φ = ω τ.

The PPD contains a 2-way power divider and 90 hybrids on a single substrate. We used the ADS Design Guide to design and generate a layout of a broadband 2-way power divider. The broadband 90 hybrid referenced in this article was previously designed and detailed in an article titled, “How to design a broadband stepped quadrature hybrid coupler in triplate stripline configuration” [1].

Theory of Operation

The incoming (unknown) RF signal is split into two from a 2-way power divider, one of which passes through a known delay, τ. These two inputs are given to a polar phase discriminator, as shown in Figure 1. Ports 1 and 5 have the inputs 2ACos(ωt) and 2ACos(ωt-φ) respectively.
Figure 1. Basic block diagram of a PPD

Figure 2 shows the action of each hybrid and the signals available at each output port. Outputs 11-12 and 15-16 are connected to matched pairs of square-law detectors.

<table>
<thead>
<tr>
<th>Ports</th>
<th>Voltage</th>
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</tr>
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<tbody>
<tr>
<td>2-10</td>
<td>$\sqrt{2}A\cos(\omega t)$</td>
<td>16</td>
<td>$A\sin(\omega t) - A\sin(\omega t)$</td>
</tr>
<tr>
<td>3-14</td>
<td>$\sqrt{2}A\cos(\omega t)$</td>
<td>15</td>
<td>$A\cos(\omega t) + A\cos(\omega t)$</td>
</tr>
<tr>
<td>8-9</td>
<td>$\sqrt{2}A\sin(\omega t) - \phi$</td>
<td>12</td>
<td>$A\cos(\omega t) + A\sin(\omega t)$</td>
</tr>
<tr>
<td>7-13</td>
<td>$\sqrt{2}A\sin(\omega t) - \phi$</td>
<td>11</td>
<td>$A\sin(\omega t) + A\cos(\omega t)$</td>
</tr>
</tbody>
</table>

Figure 2. The action of each hybrid and signals available at the output ports

The input voltages are squared and then the high frequency components are filtered during the detection process. The squared voltages and detected voltages (V1 to V4) are shown in Figure 3.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>16</td>
<td>$A^2\sin(\omega t) - 2A^2\sin(\omega t)\sin(\omega t) + A^2\sin(\omega t)$</td>
</tr>
<tr>
<td>15</td>
<td>$A^2\cos(\omega t) - 2A^2\cos(\omega t)\cos(\omega t) + A^2\cos(\omega t)$</td>
</tr>
<tr>
<td>12</td>
<td>$A^2\cos(\omega t) + 2A^2\cos(\omega t)\sin(\omega t) + A^2\sin(\omega t)$</td>
</tr>
<tr>
<td>11</td>
<td>$A^2\sin(\omega t) + 2A^2\sin(\omega t)\cos(\omega t) + A^2\cos(\omega t)$</td>
</tr>
</tbody>
</table>

Figure 3. Squared and detected voltages

The outputs of these detectors are applied to differential amplifiers to provide difference voltages, $(V2-V1) = 2A^2\sin \phi$ and $(V3-V4) = 2A^2\cos \phi$. The cosine channel is called in-phase (or I) channel and the sine channel is called quadrature (or Q) channel. These I-Q channels are connected to the X-
Y plates of an oscilloscope and when the frequency (ω is swept, the display sweeps a circle. The I/Q ratio gives the tangent, Tan φ. The correlator performs an analog-to-digital conversion, converting the two voltages into a digital word for the angle φ. Next, the delay τ, generally realized by a printed delay line (or coaxial cable), is adjusted so that a full circle (0 to 360) is swept when input frequency is swept from f1 to f2. The tangent output voltage is then digitized and calibrated with the known input frequency.

The same performance can be achieved using a 2-way power divider instead of a 180 hybrid in the phase correlator. The configuration used in this case to design the PFD is shown in Figure 4.

![Figure 4. Basic configuration of PFD used.](image)

When the input signal is swept from ω1 to ω2, delay τ is adjusted in such a way that the polar plot sweeps from φ1 to φ2 (preventing overlap and to avoid ambiguity), as shown in Figure 5.

![Figure 5. Polar plot sweep](image)

**Component Design and Simulation**

In this section, design and simulation of the diode detector, power divider and 90 hybrid are discussed. Recall that the phase correlator is a combination of a power divider and 90 hybrid.

**Simulation of Diode Detector**

As shown in Figure 6, the ADS diode model can be used to design a detector. Harmonic Balance
simulation results show detector characteristics. Similar performance can be obtained using any commercial diode model. The diode is operated in the square law region.

Figure 6. Diode detector simulation set up and characteristics

We simulated the PFD with three configurations of the phase correlator: using ideal components, using electromagnetic (EM) models of individual components, and using an EM model of a combined phase correlator.

Design of Polar Phase Discriminator Using Ideal Components
To create a polar phase discriminator, we combined an ideal 90 hybrid and ideal 2-way power divider, as shown in Figure 7a. We connected this PPD to detectors and a differential amplifier (OPAMP). The input signal was fed to an ideal power divider and one of its outputs was fed to the PPD through a tunable delay element as shown in Figure7b.

Figure 7a. Polar phase discriminator using an ideal ADS components design
To continue the analysis, the input frequency was swept from 2 to 8 GHz and the delay $\tau$ was tuned to generate a full circle, as shown in Figure 8. Notice that voltage $V_2$ is plotted against voltage $V_3$, to generate a polar graph. A small gap in the start and stop angles is intentionally set to prevent frequency ambiguity.

**Figure 8. Polar graph output of an ideal PFD (frequency sweep: 2 to 8 GHz)**

**Design of Polar Phase Discriminator Using EM models**

We designed the 90 hybrid and 2-way power divider in a triplate stripline configuration. Full EM simulations were performed on individual components and then combined to form a phase correlator.

**Designing a 90 Hybrid:** The design methodology for a 2 to 8 GHz, 90 hybrid is available in Reference 1. Its substrate dimensions are $b=67$ mil (31-5-31 mils). Figure 9 shows the layout and EM simulation results.
Designing a 2-Way Power Divider: A 2-way 4-section Wilkinson power divider covering 2 to 8 GHz can be designed using ADS Design Guides. Figure 10 shows the design parameters and the synchronized layout. The layout is EM-simulated using the ADS planar EM solver, Momentum.

Next, we generated the EM model and added resistors in the layout-look-alike EM model. The resulting power divider performance is shown in Figure 11.
Figure 11. Final 2-way power divider performance

Figure 12a depicts a triplate stripline substrate cross section. The EM models of the power divider and 90 hybrid are combined in a schematic to form the phase correlator. When simulated with this correlator, the PFD shows a distorted circle. The amplitude and phase imbalances of the power divider and 90 hybrid distort the circular shape as shown in Figure 12b.

Design of Polar Phase Discriminator Using Combined EM Models

A PPD is normally realized by integrating all components on a single substrate. This can be accomplished in ADS and with planar EM simulation as shown in Figure 13. We used a coaxial cable model for the delay line. The EM layout and PFD schematic are shown in Figure 13.
Figure 14 shows the simulated performance and further distortions to the ideal circular shape.

![Simulated performance of a PFD using a full PPD EM model](image)

**Figure 14. Simulated performance of a PFD using a full PPD EM model**

After digitizing the voltages for 1L, 2L, 4L, 8L, 16L, 32L and 64L loops, the angle \( \phi = \omega \tau \) is calibrated for input continuous wave (CW) frequencies. Lower loops are used to resolve ambiguity while higher loops are used to increase frequency resolution. Figure 15 shows delay lengths for getting 1, 2, and 4 loops. Similar performance can be easily obtained for 8, 16, 32, and 64 loops.

![Delay lengths for 1, 2 and 4 loops](image)

**Figure 15. Delay lengths for 1, 2 and 4 loops**

**Conclusion**

This article describes a design methodology for a PFD using Agilent’s ADS software. Using ideal components and delay line, a perfect circle is obtained in a polar graph, thereby verifying the theory. EM simulations take care of circuit imperfections, making the resulting performance closer to practical observations. Lower-order loops are used to resolve frequency ambiguity, while higher-order loops are used to increase the accuracy of frequency measurement.

**References**


**About the Author**

P. Sreenivasa Rao has worked as a design flow expert at Agilent Technologies for the past 6 years. He has over 25 years of experience in the design/verification of various microwave circuits and subsystems including MMICs. He holds a MTech from the Indian Institute of Technology in New Delhi, India, and a M.Sc. from the University of Hyderabad in India.