Phase Shifter Fundamentals

Telemakus USB Products

TEP2000-4
Freq Range   1-2 GHz
Insertion Loss   -4dB
Phase Range 400 Degrees

TEP4000-5
Freq Range   2-4 GHz
Insertion Loss   -5dB
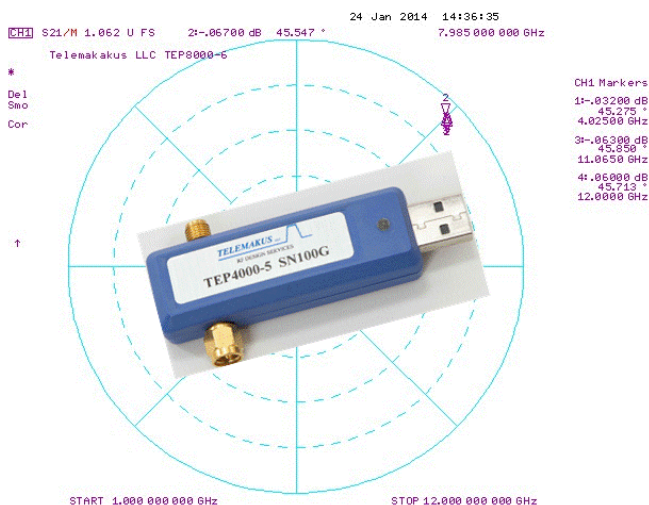Phase Range 460 Degrees

TEP8000-6
Freq Range   4-8 GHz
Insertion Loss   -6dB
Phase Range 410 Degrees

TEP12000-6
Freq Range   8-12 GHz
Insertion Loss   -6dB
Phase Range   390 Degrees

TEP18000-6
Freq Range   12-18 GHz
Insertion Loss   -6dB
Phase Range   380 Degrees

- **Greater than 360 degrees phase control**

- **12 bit DAC resolution**

- **Multiple phase shifters can be controlled from a single PC via USB**

- **Low weight at 1oz, means little or no stress on PCB connectors.**

Phase Shifters are a critical component in many RF and Microwave systems. Applications include controlling the relative phase of each element in a phase array antenna in a RADAR or steerable communications link and in cancelation loops used in high linearity amplifiers.

But what is a phase shifter? And more fundamentally, what is phase? The phase of a single tone is meaningless until it is compared to another signal. If we look at a sine wave in the time domain it would look like figure 1.
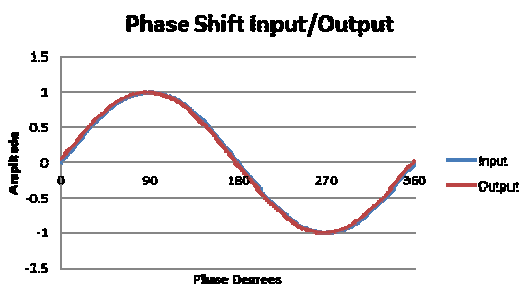
If a second sine wave is added with a 90 degree phase offset from the first it would look like figure 2.

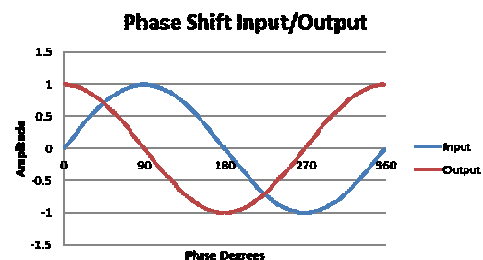Fig 2

If the phase of the second signal is varied or shifted, the sine wave is seen to move relative to the first sine wave.
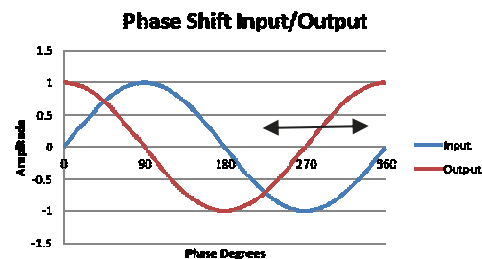

Fig 3

Fig 1

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Phase therefore is the fraction of a wavelength difference between two signals and can vary from 0 to 360 degrees. Degrees is also how we measure angles. This leads to an alternative way to view the relative phase of a signal. If we think of a single tone as having an amplitude and phase then we can depict the signal on a polar diagram as in figure 4.
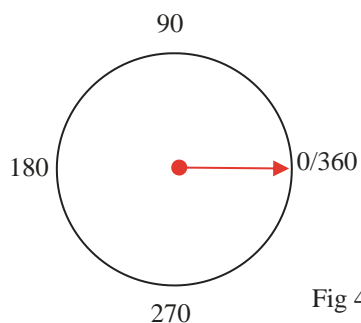

Fig 4

Fig 6

Two signals with equal amplitude and a 90 degree phase difference are shown in Fig 5. If we rotate or shift the phase of one signal then we see the signal rotate though 360 degrees around the plot.
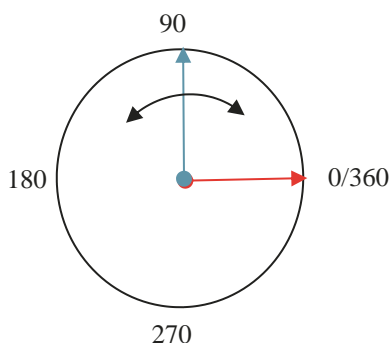
How do we build a phase shifter? A popular method uses a 90 degree hybrid and two varactor diodes configured as in figure 7 below.

Fig 5
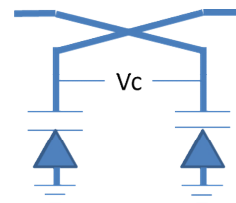
Fig 7

A varactor diode behaves like a voltage variable capacitor when it is reversed biased. The 90 degree hybrid is connected such that the coupled output is maximized when there is a total reflection of the signal at the through and isolated ports.

This leads us to one way that a Vector Network Analyzer (VNA) such as the Agilent 8720 displays phase and amplitude on a Polar Plot. See fig 6. The marker shows a 45 degree offset relative to the instruments reference tone.
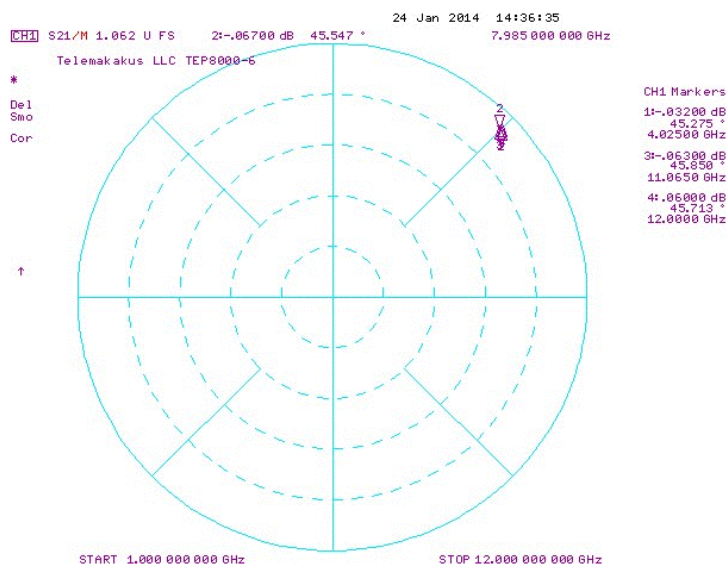
With two capacitors at these ports the power is reflected almost 100% because the capacitors are chosen to be a very low impedance at the frequency of operation. As the voltage is increased the capacitance deceases and with it the phase of the reflection. The capacitance is inversely proportional to the square root of the voltage applied and therefore the phase vs voltage function is non-linear.

A single stage as shown can have a phase range of approximately 100 degrees. Therefore to achieve a full 360 degrees, 4 stages must be connected in series. As shown in Figure 8
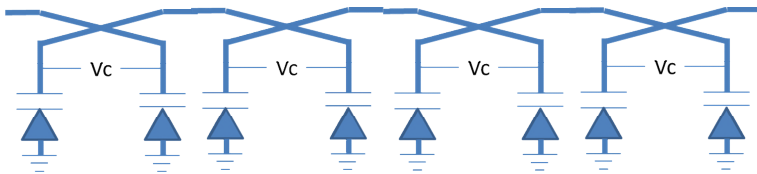

Fig 8

The insertion loss of each stage is typically around 1dB and so 4 stages will have a loss close to 4dB. This loss tends to increase as we go higher in frequency. The hybrid couplers are made using a 2 1/4 wavelength transmission lines and typically are limited to an octave wide bandwidth or less.

The Telemakus TEP2000-4 for example has a frequency range of 1-2GHz and an insertion loss of 4dB but the TEP8000-6 with a frequency range of 4-8GHz has a higher insertion loss of 6dB.

When two signals are combined with different phases the resulting signal can be described by the following expression:

$$A_c = A_1 Sin(wt+\Theta) + A_2 Sin(wt+\varphi) \qquad (1)$$

Where wt is a time varying function , Θ and φ are the two phases and A_1 and A_2 are the two amplitudes.

If we arrange for $A_1 = A_2$ and $\Theta - \varphi = 180$ then an interesting result occurs.

$$A_c = 0 \qquad (2)$$

The amplitude drops to zero and the signal vanishes. In practice, complete cancellation is impossible to achieve because of imperfections in the circuit, leakages and difficulty maintaining equal amplitude and opposite phase. However, practical circuits can easily obtain 30dB cancelation or more. This effect is in widespread use and can be found in high lower linear amplifiers. A demonstration of cancelation can be crated using a TEP4000-5 and a TEA13000-12. See figure 9.
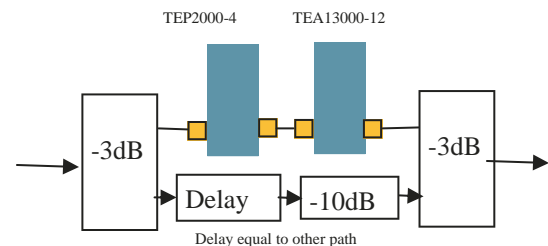

Fig 9

With this circuit measured on a VNA we can see a broadband cancellation region greater than 30dB. See Fig 10. This is a plot of S21 with attenuation and phase optimized for cancelation.
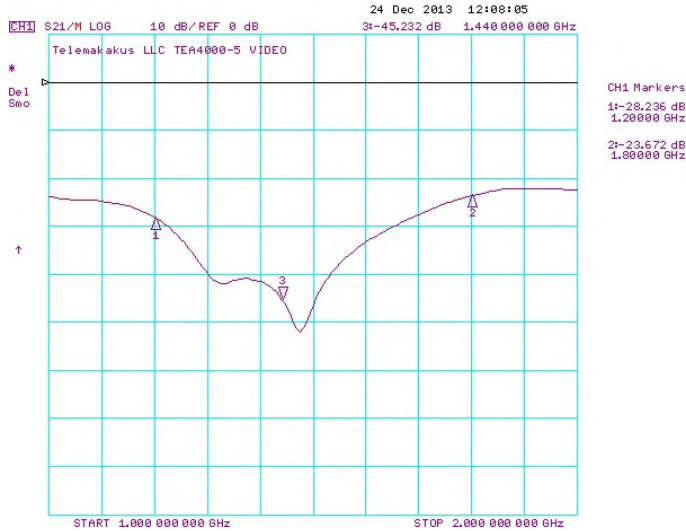

Fig 10

Another effect occurs when the amplitudes and phases are equal

$$A_C = 2A \qquad (3)$$

In this case the amplitude is doubled and is the ideal case for power combining in a high power amplifier. This is also termed constructive interference.

The diagram below shows a typical phase array antenna. In this example, 8 elements are used. Each has a dipole antenna, and a 360 degree phase shifter. A power distribution circuit provides an identical signal to each element. The direction of the combined signal can than be steered by varying the phase in each element according to a preset mathematical algorithm.
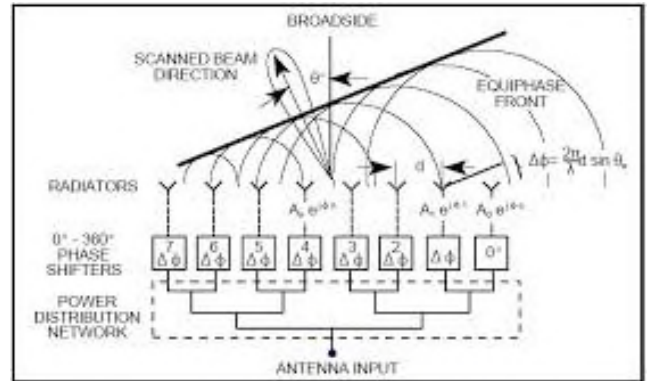

Fig 11

Critical Parameters

Insertion Loss

Amplitude variation with phase control.

IP3

Return Loss

Insertion Loss

As previously stated, the insertion loss of the phase shifter is largely driven by the number of stages needed and the frequency. 4-6dB is typical for a design with 360 degrees of control. The variation with frequency at a given phase is also critical and performance of +/-1dB over an octave bandwidth is achievable.

Amplitude variation with phase control

Another aspect of insertion loss is the variation with phase control. That is, how much does the insertion loss change as the phase is shifted. For an ideal phase shifter there would be no variation. This is important in both phase array antennas and cancelation applications because keeping

Amplitude constant means there would be no need to adjust gain as phase is changed. In a practical circuit there is going to be some amplitude variation. Over 100MHz of bandwidth this can typically to reduced to <1dB.

Third Order Intercept point or IP3

IP3 is a measure of linearity of the phase shifter. At some power level the insertion loss is going to increase creating a non-linearity. In turn this produces intermodulation products which create distortions in the spectrum of the applied signal. By definition, the IP3 is the theoretical input power that would produce third order intermodulation products equal to the power of the fundament power. This is typically measured using a two tone test where two equal amplitude signals are applied to the phase shifter and the output third order products are measured on a spectrum analyzer. Half the delta between the fundamental power and the intermodulation products is then added to the fundamental to give the IP3 performance in dBm.

IP3 = Input per tone + 1/2(Input tone -IM3)

For example if two tones are applied at 0dBm and the IM3 products are measured at –60dBm then the IP3 is +30dBm. This is a typical number for the Telemakus range of phase shifters.

Return Loss or VSWR

This is a measure of the impedance of the phase shifter. Typically 50 ohms is used as the nominal impedance of a system and the aim is to design a circuit that achieves a perfect 50 ohm match, such that all the incident power is coupled into the circuit. The return loss is a measure of the power reflected by the circuit caused by an imperfect match. A typical number for a broadband device would be –10dB to –15dB.

Control function Linearity

The control function is the relationship between the voltage or digital control value relative to the phase shift produced. Ideally this would be linear as shown in the chart below.
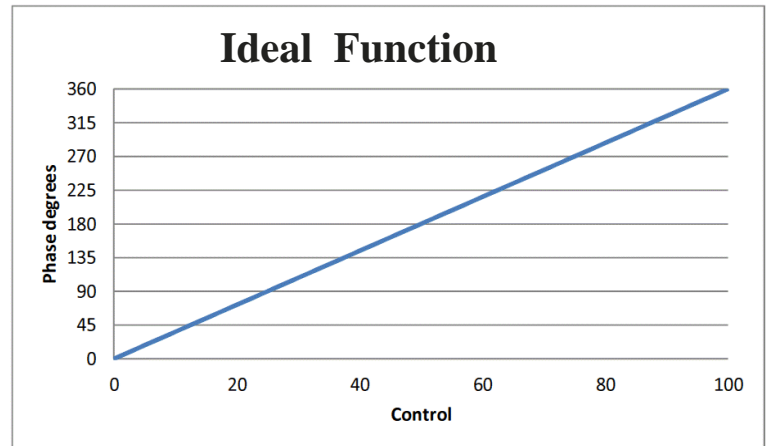

Fig 12

An actual control function would typically not be linear and look something tike the plot taken from an uncorrected digitally controlled phase shifter below.
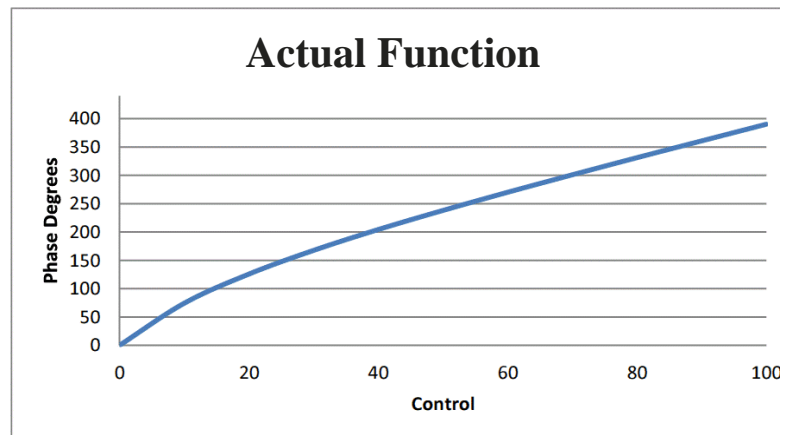

Fig 13

This non-linear function can be corrected numerically using a polynomial to represent the inverse of the actual function. The result is very close to the ideal linear function. This form of correction is coded into the GUI of each of the Telemakus Phase Shifter products.

Phase = f (actual) x f (inverse of actual) = f (ideal) (4)

The Telemakus family of Phase shifters all have 0.5MB of flash memory accessible via Windows file manager just like any other flash drive. The location will appear as the next available drive letter as shown below:
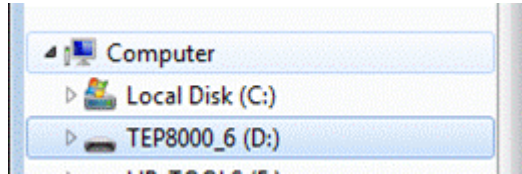
The flash is used to store a number of files that are important during the product installation and use.

The directory structure will look like the list below:

The first step in the installation process is to choose the correct version of the install files. Either 32 bit for XP or W7 32 bit or 64 bit for W7 64 bit or W8.

Selecting the right directory will open the file structure below. To run the installation, select the .MSI file and follow the instructions. When complete, the GUI files will be ready to run either from the desktop or from the program group "Telemakus LLC" under that start menu.

Double clicking on the icon will launch the GUI shown opposite.

Drive letter

Model Number

Serial Number

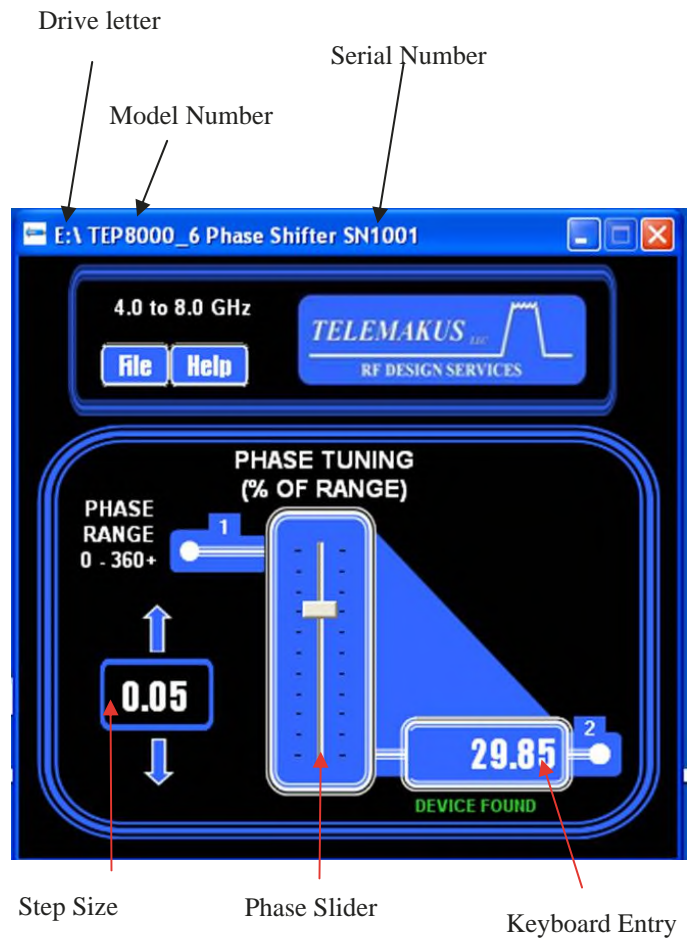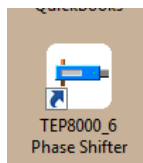Step Size   Phase Slider

Keyboard Entry

Fig 14

Conclusion

The phase shifter is a highly useful function in the world of RF and Microwave test and control. The Telemakus family of products provides an easy to use, octave wide, fine resolution, 360 degree set of phase shifters. API's are available on the flash drive for most of the popular ATE software applications such as Labview and Agilent VEE making integration into a full ATE system possible.

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