

Phase Shifters, Vector Modulators, Delay-Lines and Frequency Translators Application Notes

G.T. Microwave has amassed a wide product line of passive, analog and digital RF and Microwave Integrated Components. G.T. Microwave's analog and **digital phase shifters** are an integration of either Varactor or PIN diodes with passive circuitry. They are continuously variable analog or converted to digital control or a true digital component that is switched from state to state. This application note applies to those components related to a desired change in the phase characteristics of a signal.

- **Overview of Phase Shifters**

The function of a **phase shifter** is to control the phase characteristics in the processing of a microwave signal. This device will shift a signal to a desired phase location via a digital or analog command and can be accomplished in a passive device. In order to achieve the maximum phase shift, the circuit parameters must be chosen carefully.

A **variable phase shifter** can be characterized as a linear two-port device, which alters the phase of its output signal in response to an external electrical command. Mechanical phase shifters are not considered here. Expressing this mathematically, with the input signal $\sin(\omega t + \theta(n))$, the output will be $A(n) \sin(\omega t + \theta(n))$, where n is the programmed phase and $A(n)$ is the insertion loss. The difference between the input phase and the output phase is the sum of the phase shift due to the propagation through the phase shifter plus the programmed phase shift.

The relative simplicity of the idea that any reactance placed in series or shunt with a transmission line will produce a phase shift has given rise to many different circuits over the years for use as phase shifters at microwave frequencies.

G.T. Microwave manufactures **reactance based and switched-line phase shifters**, but also has a product line of **vector modulator based devices**. In a vector modulator based device the phase shift is accomplished by dividing the input signal, adjusting the amplitude and combining them at the output. With that said, G.T. Microwave manufactures several types of Analog or Digital Phase Shifters as well as I & Q Vector Modulators.

G.T. Microwave also manufactures passive devices that shift phase and do not require any electronic control or power consumption, which also offer fixed phase characteristics from one port to another port(s) that include, 0° Power Dividers/Combiners, 90° & 180° Quadrature Hybrids, 0°/90°/180°/270° Butler Matrix Feed Assemblies and any fixed solid state Time Delay or Phase Shift.

The final choice of a phase shifter network and control element will depend on the required bandwidth, insertion loss, switching speed, power handling, accuracy and resolution. In addition, a choice between passive, analog or digital control must also be made.

- **Variable Varactor and PIN diode based Phase Shifters, Time Delay Lines, Frequency Translators, BPSK / QPSK and I & Q Vector Modulators**

G.T. Microwave manufactures either Varactor or PIN diode based components and offers bi-directional variable phase characteristics from one port to another. I & Q Vector Modulators offer simultaneous variable attenuation.

A PIN diode is a semiconductor device that operates as a variable resistor, as the bias current changes. PIN diodes generate the least distortion, which changes the shape of the RF signal. Two different types of distortion that will occur are, intermodulation and non-linear. A non-linear distortion develops when the output signal does not have a linear relationship to the input signal. Intermodulation distortion is non-linear distortion characterized by the appearance in the output of frequencies that are linear combinations of the fundamental and any harmonics present in the input signal. Thus, PIN diodes are ideal for use in a control component for high-speed applications and high power requirements, when slower switching speed can be tolerated.

A Varactor diode is a semiconductor device that operates as a variable capacitor, as the bias voltage changes. G.T. Microwave uses varactor diodes that have high-Q's (low loss). With a variable voltage across the diode, the capacitance of the diode changes; thus, causing the reflected power to change phase. Due to the finite Q of the varactor diodes, the signal undergoes slight changes in amplitude-either increasing or decreasing-as the voltage is varied. Hyper-Abupt Varactor diodes have a relatively linear response to voltage and are the most commonly used semiconductor in analog phase shifters.

G.T. Microwave manufactures several types of these devices that include, BPSK (0° & 180°) & QPSK (0° , 90° , 180° & 270°) Modulators, Phase Shifters, Frequency Translators, Time Delay Lines and I & Q Vector Modulators with up to 16 BITS of resolution. The type of diode and the characteristic impedance of the circuit generally govern the choice.

- **Analog and Digital PIN Diode Vector Modulator based Phase Shifters, Frequency Translators, BPSK / QPSK and I & Q Vector Modulators**

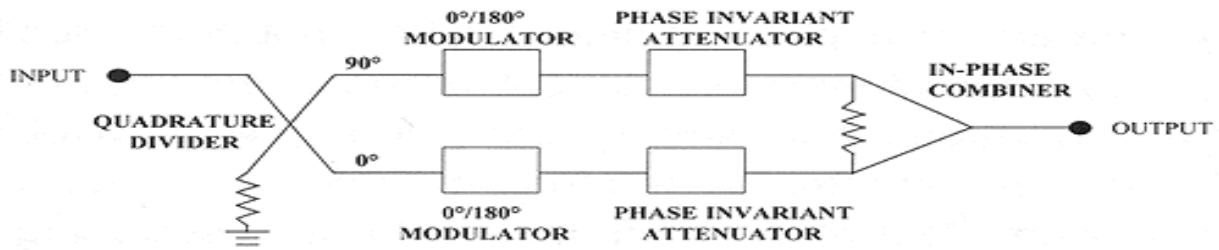
Microwave control components are used to vary signal amplitude and phase. Typically, they consist of two-port devices including amplifiers, attenuators, phase shifters and switches. The I & Q vector modulator is a unique combination of active and passive devices that is, in theory, ideally suited for the simultaneous control of amplitude and phase.

The function of a vector modulator is to simultaneously control the phase and amplitude characteristics in the processing of a microwave signal. This device will convert a signal to a desired vector location via an electronic command and the RF, being an analog circuit, offers unlimited resolution capability.

Any sinusoidal signal can be expressed as a vector having the properties of both amplitude and phase with respect to a reference signal. If a signal is thought of as a vector in a polar coordinate system with coordinates of amplitude and phase, it can also be defined in a rectangular coordinate system as "I" and "Q". The term "I & Q" represents the "In-Phase" and "Quadrature-Phase" components of the output signal.

The theory of operation is to divide the input signal into two equal signals 90° apart, I & Q. This allows the magnitude of each signal to be re-located along its vectors' axis. The two signals are then combined. Using the Pythagorean theorem, the sum of the vectors produces the resultant output signal.

The circuit for this device consists of nine 3 dB, 90° Quadrature Hybrids, two Variable Attenuators capable of a 180° phase shift, an In-Phase Power Combiner and drive circuits to control the variable attenuators.



I & Q VECTOR MODULATOR BLOCK DIAGRAM

The input signal is processed by the first hybrid. It equally divides the amplitude with a 90° phase shift to the quadrature path, as the two signals are isolated. This places the I & Q Vectors on their respective axis. The balances of the hybrids are divided in the I & Q channels for the variable attenuators. Each attenuator controls the magnitude with 180° phase shift allowing four-quadrant operation. The final stage is the In-Phase Power Combiner, which combines the signals in the vector addition to the output.

If the doubly balanced bi-phase-modulator control conditions are adjusted so that the magnitude of the resultant vector remains fixed, the I & Q vector modulator can behave as a constant-amplitude phase shifter.

The relationships between desired phase shift and I & Q attenuation levels are given by:

$$|I|^2 + |Q|^2 = 1$$

$$I = \cos \theta$$

$$Q = \sin \theta$$

where I & Q are normalized voltages.

This technology yields an overall improvement in both Phase Flatness Vs Frequency and produces up to 9:1 Bandwidths. G.T. Microwave hosts a variety of products that include, BPSK, QPSK and I & Q Vector Modulators, Phase Shifters, Frequency Translators and Phase Free Attenuators.

G.T. Microwave offers models in frequencies from 250 MHz to 24 GHz and options that include, Ultra-Broadband, Optimized Narrowband, Analog, and Digital Control with up to 64K of resolution and sub-assembly integration. Additionally, they are bi-directional devices.

- **Digital PIN Diode Switched-Line Phase Shifters, BPSK / QPSK Modulators and Time Delays**

Digital Phase Shifters and Digital Time Delays are designed to be controlled directly from a TTL circuit. Phase shift or Time delay is provided in binary sequenced increments from LSB (least significant bit) to the MSB (most significant bit) and in digital switched sections for the optimum absolute accuracy.

This technology yields high-speed devices having a phase slope that is linear with frequency and is resilient for severe environments.

This technology hosts a variety of products that include, BPSK / QPSK Modulators, Phase Shifters, Time Delays and Phase Free Attenuators. Models are available for frequencies from 500 MHz to 24 GHz in optimized narrowbands and sub-assembly integration. Additionally, they are bi-directional devices

- **Analog Varactor Diode based Phase Shifters**

Analog continuous variable Phase Shifters consist of a technique using balanced, hybrid coupled varactor diodes. The actual phase shift is comparatively constant over the frequency range, and is controlled either by carrying the analog bias voltage, or by issuing a digital command through a digital-to-analog converter. Drive circuits can be designed to enable the device to change phase states rapidly, and, when used in conjunction with a PIN diode attenuator, the amplitude ripple is negligible.

If lossless susceptances of equal phase and magnitude are placed at the outputs of a 4 port, 3 dB hybrid coupler, all of the energy entering the input will exit through the isolated port. Since none of the power is reflected back to the input, theoretically the V.S.W.R. is 1:1. If the susceptances are replaced by high-Q varactor diodes, the circuit operation is the same. With a variable voltage across the diode, the capacitance of each diode changes; thus, causing the reflected power to change phase.

For example, high-Q varactor diodes with a capacitance ratio of 4:1 can produce a phase shift of approximately 75°. If the normalized susceptance of a diode in a 50-ohm system changes from 0.5 to 2.0 its phase change is about 75°. However, if a shunt inductance is positioned across the diode, it's possible to provide a phase shift of nearly 150°.

This technology yields a very high-speed phase shifter that operates at low RF power and has a relatively Flat Phase Vs Frequency. Analog phase shifters are continuously variable as the control input voltage is changed; therefore, offering unlimited resolution with monotonic performance.

G.T. Microwave manufactures several Analog Phase Shifters that include, 60°, 90°, 180° or 360° of phase shift. Models are available for frequencies from 500 MHz to 18 GHz in octave and optimized narrowbands and sub-assembly integration. Additionally, they are bi-directional devices.

- **Overview of Frequency Translation**

A signal-processing technique using a linear time-varying phase shifter is one method of frequency translation. Frequency translators are comprised of fast switching digital phase shifters. The input binary word advances or retards the phase in discreet increments. The device is switched periodically through 360 degrees in increments that are equal to the LSB. The frequency translator converts the frequency of an RF carrier to a lower or higher frequency.

One principal use is in velocity deception for ECM systems by providing false Doppler radar returns. In a true Doppler radar situation, the reflected signal is translated in frequency in an amount proportional to the radial velocity of the target. As a rule, there are no harmonics or spurious signals accompanying the reflection. However, if the target is using velocity-deception techniques, spurious signals may be present in the radar return because of the non-ideal performance of the frequency translator. The presence of these spurious signals will reveal that the Doppler radar is being jammed. Therefore, it is critical for

optimum ECM system performance that the frequency translator suppresses the carrier, harmonics and all unwanted sidebands to the greatest extent possible. For the linear phase shifter, the principal factors that contribute to imperfect carrier suppression and sideband generation are:

2 Π error: This is the deviation from 360° when maximum phase shift is programmed.

PM/AM error: The amplitude change (AM) is a function of the phase change (PM).

Phase nonlinearity: It is the deviation from linear phase shift vs. time.

Quantization error: This term is usually negligible for phase resolution greater than 6 bits. It arises in a digital phase shifter, which only approximates linear phase shift with discrete phase steps.

Special attention in the design of the units has been paid to those characteristics that affect their performance as frequency translators. These include minimizing PM-to-AM conversion, use of high slew rate drivers and optimizing phase shift linearity with applied signal. As a result, carrier and sideband suppression levels of over 25 and 20 dB, respectively, are obtained across the entire frequency range.

- **Overview of Passive Phase Shift Devices**

A 3 dB $0^\circ/90^\circ$ Quadrature Hybrid Coupler will combine or divide a signal and offer in-phase as well as a differential of 90° . A signal applied at the input port appears at both output ports in phase quadrature. If two signals in phase quadrature are applied to each of the output ports, they will add at the input port and cancel at the isolated port. If the two signals are interchanged at the output ports, they will add at the isolated port and cancel at the input port. G.T. Microwave's 3 dB Hybrid Couplers are balanced by directional devices such as switches, imageless mixers, balanced amplifiers, PIN Diode attenuators, phase shifters, single sideband modulators and many others.

A 3 dB or $0^\circ/180^\circ$ Quadrature Hybrid Coupler consists of a conventional 90° hybrid plus a broadband 90° phase shifter. Depending on which input is used, the two output signals are either in phase or 180° out of phase. These hybrid couplers can handle large amounts of CW power since they do not employ internal resistors. These devices can be applied to power dividers, power combiners, balanced mixers, image rejection mixers, antenna feed networks, single sideband modulators, matrix amplifiers and switching networks.

- **G.T. Microwave phase shifters host a variety of applications:**

The popularity of high-speed diode phase shifters is exemplified by their increased use in today's state-of-the-art radars. They are used in serrodyne systems where swift phase changes result in nearly pure sideband generation. Serrodyning is a prevailing electronic countermeasures (ECM) technique used to prevent CW or Doppler tracking radars from gaining accurate velocity information. A phase modulator capitalizes on the transit-time modulation of a traveling-wave tube or klystron. Sweeping the phase shifter with a sawtooth causes the RF signal phase to change; it produces an FM signal. It's a modulation technique that is characterized by a very low carrier and a large single-sideband. Phase shifters are also adapted to phased-array antennas to scan multiple targets, and in frequency-agile systems where frequency and phase must change quickly. With the increased use of microprocessors in radars, "fast" phase shifters will find expanding applications in the following systems:

Phase array antenna systems
Antenna test
Simulation technology
Frequency translation
Frequency serrodyning
Feedback loop for canceling intermodulation products in amplifiers
Noise cancellation systems
QAM modulation for communications
Radar systems
Complex I & Q vector modulation
Antenna calibration
Deep space surveillance
Smart antennas

- **G.T. Microwave I & Q Vector Modulators host a variety of applications:**

Amplitude and Phase control for RF simulator systems
Quadrature Amplitude Modulation
Cancellation of unwanted jamming signals
Doppler Simulation
Nulling of antenna reflections in monostatic radar systems
Complex weights for Phased Array Antennas
Linear Filter Equalizer

It's important to note that the insertion loss of any phase shifter should be kept as low as possible. High losses will cause a reduction in transmitted power and a lower signal-to-noise ratio in the receiving section of the best radars.