LINEAR ANALOG HYPERABRUPT VARACTOR DIODE PHASE SHIFTERS

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ABSTRACT

Design and performance of analog phase shifters using hyperabrupt varactors with linear phase versus voltage is presented. Phase linearity of 22 degrees per volt ±8 percent was achieved for a 100 degree S-band device with a phase deviation of 1 degree from linearity. At X-band, linear phase control of 270 degrees was achieved. The selection of the varactor diode capacitance versus voltage and matching circuits for linear performance are presented.

INTRODUCTION

The linear analog phase shifter permits high phase resolution with a simple microwave circuit and has applications for advanced control functions. The varactor diode is well adapted for this application since it offers rapid response of phase to a voltage command. Additionally, the doping profile of the varactor can be controlled to achieve hyperabrupt junctions with a large capacitance change and a constant capacitance-voltage slope exponent (gamma) [1]. The constant-gamma varactor offers the potential for large shifts with linear phase versus voltage.

Numerous investigations of the analog phase shifter have been performed. Dawson [2] used the gate-to-source capacitance of the FET to achieve analog phase shift. Ulriksson [3] and Hopfer [4] developed techniques for constant phase versus frequency for abrupt diode junctions. Mains [5] investigated varactor voltage shaping and diode doping profiles to achieve linear phase, while Garver [5] developed circuits for linear analog phase using graded and abrupt junction varactors. This paper presents new linear phase results using constant-gamma hyperabrupt varactors.

This investigation will consider the reflection type phase shifter. For this circuit, varactors terminate two of the four ports of a 90 degree hybrid coupler, or a single varactor can be coupled to a three-port circulator. The phase shift depends upon two functions, namely, the capacitance-voltage of the diode and the circuit phase-capacitance. The interrelationships between the varactors' gamma and the circuit impedance on linearity will be analyzed, and circuits to linearize the overall circuit will be reported. Design details and test data will be presented for linear analog S- and X-band phase shifters.

LINEAR PHASE ANALYSIS

The varactor diodes' capacitance (C) versus voltage (V) is a function of the junction doping distribution as indicated by the diodes' gamma (γ) as follows:

$$C = \frac{C_{jo}}{(1 + V/\Phi)^{\gamma}}$$

where

C_{jo} = constant
Φ = contact potential of diode

The hyperabrupt can be fabricated to have a constant gamma over limited voltage ranges from 1 to 2 with a high capacitance variation. Figure 1 illustrates the measured C-V curve for such a diode manufactured by M/A-COM that exhibits a constant gamma of 2 from 3.5 to 7.5 volts. Outside this voltage range, the gamma decreases significantly.

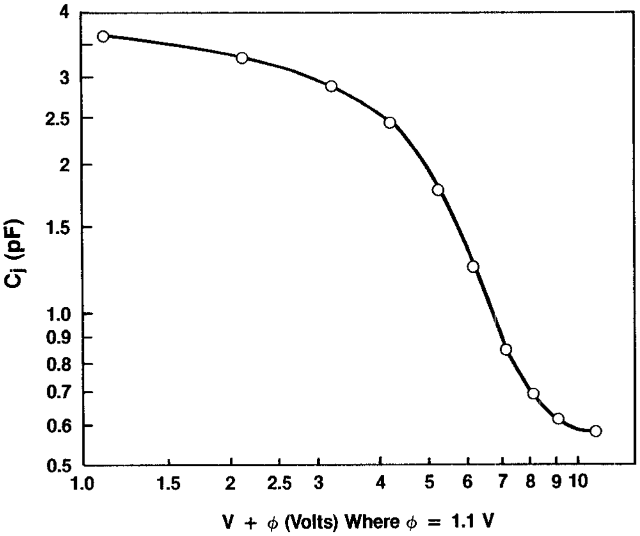

Figure 1. Capacitance Versus Voltage for Hyperabrupt Tuning Diode

The phase shift for a diode terminating a transmission line of characteristic impedance Z_o for a reflective phase shifter is:

$$\Phi = -\Pi + 2\tan^{-1}(x_d)$$

where

$$x_d = \frac{1}{\omega C Z_o} = \frac{(1 + V/\Phi)^{\gamma}}{\omega C_{jo} Z_o}$$

ω = angular frequency

The phase change with applied voltage is best understood by examining the Φ versus x_d and x_d versus V functions. The first (Φ) function has an inverse tangent relationship and is linear only for small values of x_d. This condition would be useful only if small phase shift values are of interest. For a large phase shift range, the slope of Φ versus x_d continuously decreases with increasing values of x_d or V, reaching a saturating phase value of 0 degrees. The slope of the second function, x_d versus V, is constant with voltage for gamma = 1, continuously increases with voltage for gamma greater than 1, and continuously decreases with voltage for gamma less than 1. It becomes apparent that linear phase can be achieved only for gamma values greater than 1 for the diode circuit (no

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additional tuning elements) since the compression of $d\Phi/dx_d$ is compensated by the expansion of dx_d/dV over a wide voltage range by selection of the ωCZ_o range for a specific gamma.

Figure 2 illustrates the computed phase shift versus voltage for various diode gamma values for a 2.85:1 capacitance ratio with $\omega C_{max}Z_o$ = 2. The value of C_{max} at 4 volts was assumed identical for all curves. The phase shift linearity is improved dramatically as gamma is increased. As

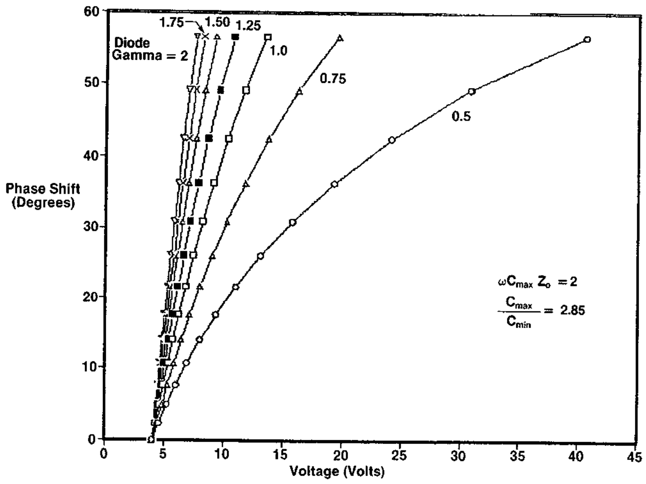

Figure 2. Computed Phase Shift Versus Voltage Versus Diode Gamma

expected, an optimum value of $\omega C_{max}Z_o$ exists for a particular diode for gamma values greater than 1. Figure 3 illustrates this point for a 1.75 diode gamma. High linearity exists for $\omega C_{max}Z_o$ = 3. Higher values of this parameter cause the curves to be concave upward, while lower values result in a concave downward characteristic. Linear operation does result for a 2:1 frequency range by operating on the $\omega C_{max}Z_o$ values of 2 to 4. In this region the phase deviation from linearity is 1.4 degrees maximum for a nominal 50-degree phase shift over the octave band.

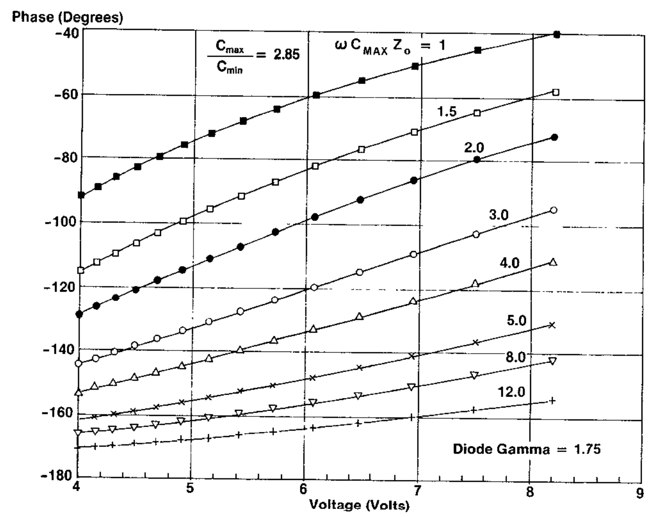

Figure 3. Computed Phase Shift Versus Voltage; Diode Gamma = 1.75

The phase shift can be increased and linearized by adding to the circuit a series inductor (L) with normalized reactance $x_L = \omega L/Z_o$ as shown in figure 4. The phase curve is concave downward with 56.6 degree phase shift with no inductance. Adding an inductive reactance (x_L = 1.65) that is 25 percent less than the value for series resonance at the center operating voltage results in a linear response with an in-

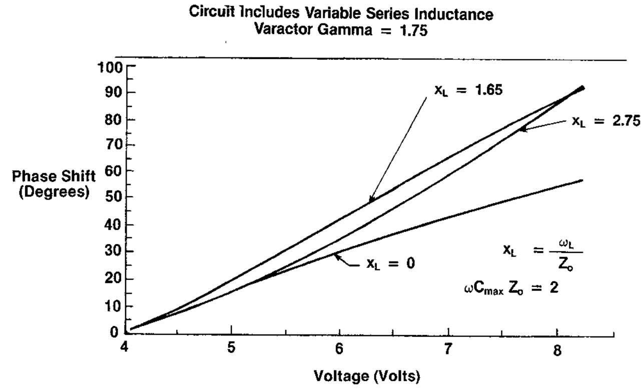

Figure 4. Computed Phase Shift Versus Voltage With Series Inductance

creased phase shift range of 92.2 degrees. Further increase of inductance (x_L = 2.75) results in a concave upward phase response.

The results of the previous circuit suggest that linearization of a diode with a gamma less than 1 can be accomplished by selecting the inductance value, which is indeed the case as shown in figure 5. The very nonlinear curve for gamma = 0.5 is substantially linearized by adding x_L = 2.0.

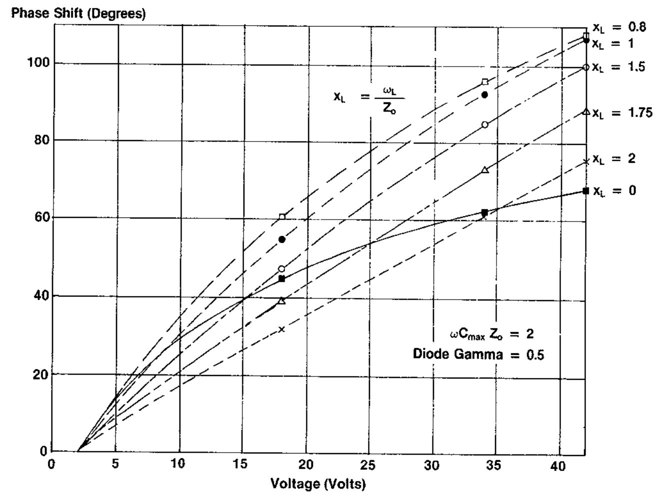

Figure 5. Computed Phase Shift Versus Voltage; Abrupt Diode With Series Inductance

DEVELOPMENTAL LINEAR PHASE SHIFTERS

A 100 degree analog phase shifter was developed on high dielectric (ϵ_r = 10.1) soft microstrip using a pair of hyperabrupt diodes coupled to a branch line coupler with series inductance and a 40-ohm quarter-wavelength transformer as seen in figure 6. The GaAs diode with a gamma of 1.8 and a junction capacitance at 4 volts of about 2 pF were packaged in a low parasitic capacitance M/A-COM ODS120 package (C_p = 0.12 pF, L_s = 0.3 nH). The quarter-wavelength line increased the overall phase shift to the 100 degree requirement. The entire circuit was modeled and the inductance was selected for linear phase response.

Figure 7 illustrates the measured and calculated phase shift versus bias voltage. The measured phase slope was 22 degrees/volt ± 8 percent over the 100 degree phase range with a phase deviation from linear of 1 degree. The VSWR was 1.3:1 maximum with a total loss of 2.0 dB. The parasitics of the package did not degrade the phase linearity, with excellent agreement between the calculated and measured phase-voltage responses. As can be seen, the linearity was excellent and did not require empirical adjustments of the circuit inductance or quarter-wavelength

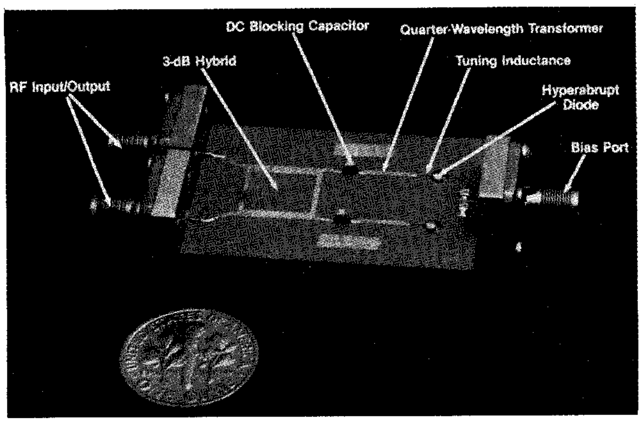

Figure 6. S-Band Analog Phase Shifter

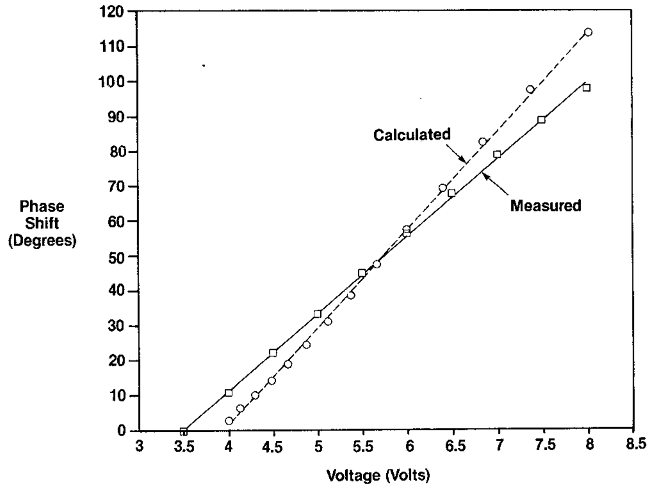

Figure 7. S-Band Analog Phase Shifter Phase Shift Versus Voltage

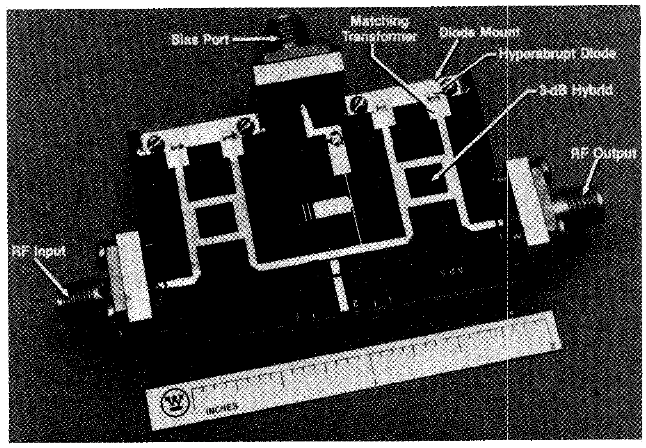

Figure 8. X-Band Hybrid-Coupled Analog Phase Shifter

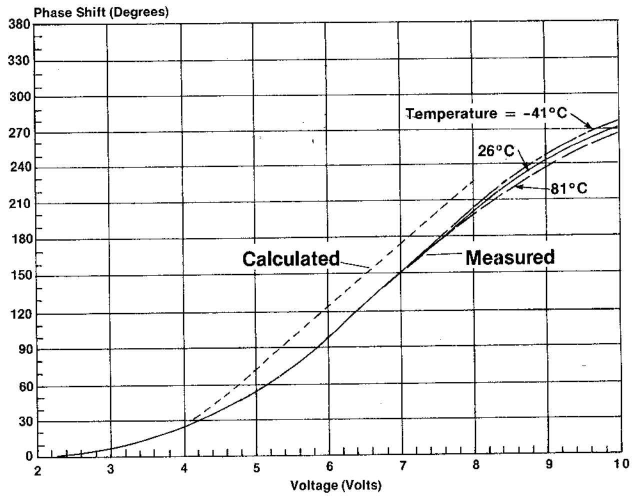

Figure 9. X-Band Hybrid-Coupled Analog Phase Shifter Phase Shift Versus Voltage

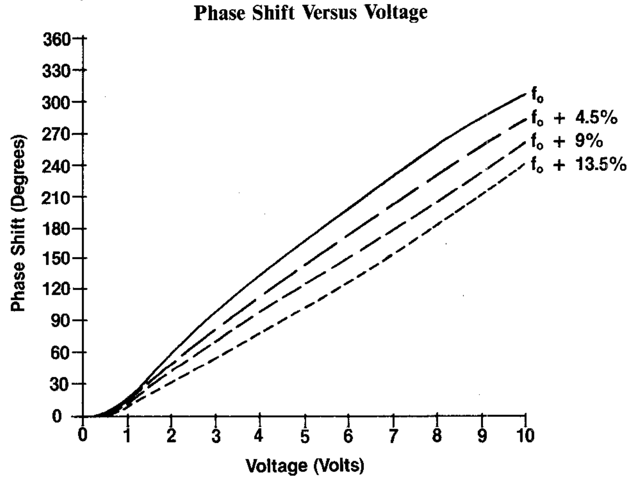

Figure 10. X-Band Circulator-Coupled Analog Phase Shifter Measured Phase Shift Versus Voltage

transformer. If the phase versus voltage is concave downward, the tuning inductance value would be increased for linear phase, while the converse is true for concave upward phase versus voltage. These adjustments are readily made in microstrip by trimming the width of the line.

An X-band 270-degree analog phase shifter was developed on a low-dielectric soft microstrip with a two-stage integrated hybrid coupled circuit as shown in figure 8. The diodes were similar to those used on the S-band unit. At X-band, the diode with its connecting strap is inductive for high bias voltages and approximately series resonant at the lower bias point with a linear phase shift of 37 degrees for a 4 volt range in 50 ohms. A phase shift of 100 degrees was obtained using a 25 ohm transformer whose length was analytically optimized to achieve linear phase. This transformer circuit can linearize a circuit just as an inductor circuit can by the proper selection of the location of the impedance change with respect to the circuit impedance.

Figure 9 illustrates the measured and calculated overall response of the two stage integrated phase shifter with a very linear 200-degree response over the range 5 to 9 volts. The phase shift was insensitive to temperature for voltages under 8 volts as seen in figure 9, and showed a 10 degree maximum change from −41°C to 81°C for voltages greater than 8 volts.

A two-stage X-band microstrip circulator-coupled phase shifter was also developed using Alpha Industries GaAs hyperabrupt tuning diodes. These diodes had a nominal gamma of 1.4. The matching circuit was similar to that of the hybrid-coupled X-band unit described earlier. Figure 10 illustrates the phase shift versus voltage and frequency. Over the 2 to 10 volt region, a phase shift of 220 deg ± 10 deg was achieved with a maximum phase deviation from linearty of 7 deg for 13.5 percent bandwidth at X-band. As is expected, the linearity is best at the center operating frequency, whereas at the band edges the phase versus voltage is either concave upward or concave downward.

Figure 11 illustrates the phase shifter's insertion loss versus frequency and voltage. The total loss modulation was 1.7 dB maximum over the 2 to 10 volt region. The nominal 4 dB loss includes the 1.6 dB of circulator losses.

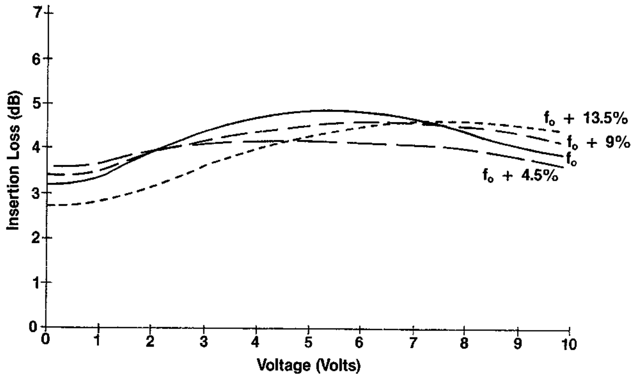

Figure 11. X-Band Circulator-Coupled Analog Phase Shifter Measured Insertion Loss Versus Voltage

The circuits were installed in phase locked loops and operated with +20 dBm input power with excellent dynamic characteristics. Operation at even higher power levels is possible by using a series connection of back-to-back diodes. This configuration doubles the phase shift and minimizes forward conduction under high power.

CONCLUSION

Hyperabrupt diodes combined with linear matching circuits have led to high performance and reproducible linear analog phase shifters from S-band to X-band.

REFERENCES

1. A.E. Moysenko and C.A. Barratt, "Computer Aided Design and Manufacture of GaAs Hyperabrupt Varactors," *Microwave J*, Mar 1982, pp. 99-103
2. D.E. Dawson, A.C. Conti, S.H. Lee, G.F. Shade, and L.E. Dickens, "An Analog X-Band Phase Shifter," *IEEE 1984 Microwave and Millimeter Wave Monolithic Circuits Symposium, Digest of Papers,* pp. 6-10
3. B. Ulriksson, "Continuous Varactor-Diode Phase Shifter With Optimized Frequency Response," *IEEE Trans. Microwave Theory Tech.*, July 1979, Vol. MTT-27, pp. 650-654
4. S. Hopfer, "Analog Phase Shifter for 8-18 GHz," *Microwave J*, Mar 1979, pp. 48-50
5. R.K. Mains, G.I. Haddad, and D.F. Peterson, "Investigation of Broad-Band, Linear Phase Shifters Using Optimum Varactor Diode Doping Profiles," *IEEE Trans. Microwave Theory Tech.*, Nov 1981, Vol. MTT-29, pp. 1158-1164
6. R.V. Garver, "360 Degree Varactor Linear Phase Modulator," *IEEE Trans. Microwave Theory Tech.*, Mar 1969, Vol. MTT-17, pp. 137-147