LINEAR ELECTRONIC PHASE SHIFTER DESIGN*

H. Schwarz

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

1. Introduction

The RF systems for linear accelerators or storage rings use electronically variable phase shifters as control elements in feedback loops or to set reference phases. A variety of electronic phase shifters has been described in literature^(1,2,3,4) One desirable feature of these devices is a linear response of the phase shift as a function of their control voltage. This report describes the design of 180° phase shifters at 1300 MHz and 353 MHz using voltage variable capacitance diodes as terminations in transmission lines. The optimization of parameters is discussed with emphasis on linearity, power handling capability and temperature stability.

2. Basic Design Principles

If a transmission line is terminated in a voltage variable capacitance diode (VVC), the phase of the reflected signal on the transmission line can be varied by changing the bias voltage on the diode. An increased phase range can be achieved by adding an inductance either in parallel or in series with the VVC and thus creating a tunable resonant circuit. The phase of the reflection, θ , from this resonant circuit, neglecting loss and stray reactances, is given by:

$$\theta = -2 \arctan \frac{X}{Z_0}$$

where

$$X = -\frac{1}{\omega C_T} + \omega L$$

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for a series resonant circuit. ω is the angular frequency of operation, L is a fixed inductance and Z_0 is the characteristic impedance of the transmission line. The capacitance, C_T of the voltage variable capacitance diode as a function of the bias voltage, V , is given by:

$$C_T = \frac{C_0}{(1 + \frac{V}{\phi})^\gamma}$$

C_0 is the capacitance at zero bias. The contact potential, ϕ , for most VVC diodes is on the order of 0.6 to 0.7 volts and the exponent γ on the order of 0.47.

Robert V. Garver in his paper⁽³⁾ points out that the nonlinear nature of the capacitance versus bias voltage can over a certain range be matched to the tangent function of phase shift for both parallel and series configurations. Thus, by properly selecting C_0 and L , a nearly linear phase response can be achieved. A fixed lumped capacitor, added across the transmission line between the terminating resonant circuit and the generator was found to be helpful in optimizing the linearity of the phase shifters. The effect on the phase shift varies depending upon the capacitors position along the transmission line. If the capacitor is located at a minimum of the voltage standing wave, it will not contribute to reflections or the phase shift of the device. Whereas, it will have an increasing or decreasing effect on the phase shift when it is not at a voltage minimum position. Since the voltage minimum shifts with the phase shift, the effect of the capacitor varies over the phase shift range.

The selection of the proper component values is described in the next paragraph.

It should be mentioned here that in order to use the circuit as outlined above for a transmission type phase shifter, the reflected RF signal has to be separated from the incident RF signal which can be accomplished with a ferrite circulator or by terminating each of the two output ports of a 3 dB coupler or hybrid with one of the phase shift circuits. Also, appropriate filter networks are required to separate the RF signal and diode bias signal.

3. The Design of a Shunt-Tuned Phase Shifter at 1300 MHz

Numerous 200° continuously variable phase shifters at 1300 MHz were required for the feedback and control circuits of the superconducting Accelerator under development at the High Energy Physics Laboratory at Stanford. A high power handling capability of up to 5 watts CW, as well as good linearity, was desired for phase shifters in the drive chains of 10 kW CW klystrons. The phase shifters to be used in the phase reference line of the same accelerator had to handle power levels below 1 mW, but had to be linear and very insensitive to temperature variations.

A VVC diode with a breakdown voltage of 120 V was selected in order to accommodate the high RF voltage.

The parallel resonant configuration with resonance occurring at high bias voltage was chosen to make use of the reduction of RF voltage swing across the diode at small bias voltages, where the resonant circuit appears like a short circuit to the $50\ \Omega$ transmission line. This way the condition where the RF voltage drives the diodes into forward conduction occurs at lower bias levels and a larger range of bias voltage can be used.

To choose the proper capacitance and inductance relatively simple computer calculations were performed using the equivalent circuit in Figure 1 to calculate the phase shift of the reflected signal versus bias voltage. The parameters of available diodes were used and a number of curves of phase shift versus bias voltage with the capacitance of the VVC and the inductance L as parameters were produced. From this collection of curves the most linear response with a 200° range was selected. A VAT-19⁽⁵⁾ was chosen which has a capacitance of 40 pF at 0 volt and a $Q = \frac{1}{R\omega C} = 450$ at 4 V and 50 MHz, $\phi = 0.7$ V, $\gamma = 0.46$ mounted in a pill package.

The parallel inductance could be simulated by an appropriate length of $50\ \Omega$ line with a trim capacitor as a termination. The circuit invites itself for layout in the microstrip technique where it is

Fig. 1. Parallel Resonance Equivalent Circuit.

also simple to include a 3 dB hybrid. Since the power in this case is divided into 2 arms of the phase shifter this adds another advantage for the high power applications. A simple stopband filter was designed to isolate the RF from the bias input. The circuit was laid out on 1/16 inch teflon glass⁽⁶⁾ board and matched pairs of diodes were used for the two arms of each phase shifter (Figure 2).

The agreement between the measured phase shift at low power and the calculations is remarkably good (Figure 3).

Figure 4 shows the calculated and measured insertion loss where the latter includes losses in the printed circuit board and DC block capacitors and therefore is higher than calculated. It also shows the typical VSWR.

The RF voltage superimposed on the DC bias voltage for 5 watt operation is shown in Figure 5. Forward conduction sets in at a bias of -2 V so that the lower limit of bias voltage was set to -5 V. At the -120 V bias point where the peak RF voltage can drive the diode into breakdown, it was observed that the effective RF voltage for start of breakdown is about a factor 3 times smaller than the actual RF voltage due to its fast change of sign. Therefore, the phase shifter using diodes with a typical breakdown voltage of 135 V could safely be operated at 5 W. Harmonics produced at the 5 W power level were measured to be 40 dB below the signal level. One problem encountered with this phase shifter operating at the 5 watt level was a parametric oscillation where both diodes interacted with each other via the bias connection. This effect occurred at approximately -15 V bias and greatly increased the insertion loss besides producing several lower frequencies. The effect disappeared when 100 Ω decoupling resistors were added in series with the bias connections. The temperature coefficient of the phase shifter operating at low power was measured to be +0.06 degrees/ $^{\circ}\text{C}$ at 30 $^{\circ}\text{C}$.

Fig. 2. 1300 MHz Phase Shifter Circuit.

Fig. 3. Phase Shift versus Bias.

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Fig. 4. Insertion Loss and Typical VSWR vs. Bias.

Fig. 5. RF and Bias Voltage Across VVC Diode.

4. The Design of a Series-Tuned Phase Shifter at 353 MHz

The RF system for the positron-electron storage ring project (PEP) at SLAC uses electronically controlled phase shifters with a 180° range and for RF power up to 10mW for a variety of functions in its feedback and control electronics. For this application selective calculations were performed for both shunt and series tuned circuits and a solution for a series resonant circuit was found using a IN5461⁽⁷⁾ diode in a glass package with a capacitance of 6.8 pF at 4 V, a $Q = 600$ at 4 V and 50 MHz, $\phi = 0.6$ V, $\gamma = .47$ and a breakdown voltage of 30 V. The shunt tuned circuit would have required a larger capacitance and parallel operation of several diodes, and thus was considered less practical. The calculations were all performed on a programmable hand calculator (HP 25) based on the equivalent circuits in Figures 1 and 6.

The phase shifter was built again in microstrip techniques on 1/16 inch teflon glass board.⁽⁸⁾ Because of the low frequency a printed circuit 3 dB hybrid would have been rather large, so a commercial, plug-in type, hybrid⁽⁹⁾ was used instead. Lumped components were used for the low pass filter for the bias input. The series inductance consisted of 3 turns of 20 AWG wire and thus could be optimized by changing its length. Early tests indicated that the purchased diodes had somewhat different parameters than those quoted by the vendor. Further optimization was needed in the form of additional 5.6 pF capacitors placed 0.05 wavelengths away from the resonant circuit described in section 2 of this report. The position and size of this capacitor was determined empirically by sliding different size washers along the top trace of the 50 ohm line between the 3 dB hybrid and the resonant circuit, while optimizing the total phase shift and checking the linearity. The total phase shift could be increased by adding this parallel capacitance and eventually an almost linear response over a bias voltage from 0 to 10 V was achieved.

Figure 7 shows the final circuit layout and Figure 8 the measured phase shift and insertion loss versus bias voltage. The phase shifter operates up to a power level of 10 mW with its bias variable from 0 to

Fig. 6. Series Resonant Equivalent Circuit.

Fig. 7. 353 MHz Phase Shifter Circuit.

Fig. 8. Phase Shift and Insertion Loss vs. Bias.

10 volts. Second harmonic production is 40 dB below the signal level and the VSWR is typically, 1.2. The temperature coefficient was measured to be 0.04 degrees/°C.

Operation of this phase shifter at higher power levels becomes increasingly difficult since the RF voltage across the diode in the series resonant configuration is increased over the input voltage by the Q ratio of the resonant circuit. This causes dependence of the phase shift on the power level and increases higher harmonic production.

Figure 9 shows a module using 3 phase shifters in series to create a 0 to 540° phase shifter, which is being used as part of the phase feedback loop in the drive chain to the PEP 500 kW CW klystron.

5. Conclusion

Both parallel and series resonant circuits can be used for linear phase shifters at power levels below 10 mW. For power levels above 100 mW the parallel resonant configuration has definite advantages and should be used. At power levels above one watt, diodes in pill packages should be used which can provide better heat dissipation through thermal conductance compared to glass packages. In all cases the total phase shift can be increased and the linearity improved by careful choice and positioning of the shunt, lumped capacitor discussed in section 2.

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Fig. 9. 353 MHz 540° Phase Shifter Module.

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