A Voltage-Controlled Phase Shifter

Contest Winner Provides Design Flexibility for Phase-Sensitive Designs

By Thomas R. Mathews
Wavetek RF Products, Inc.

Many of today's complex systems require the ability to control the phase relationship of two signals. Typical applications include delay line descriminators, phased antenna networks and oscillators. Quite often these systems are realizable with fixed delay networks, but for many applications there is a need to provide a voltage-controlled phase shift. The design presented here won the author a runner-up prize in the Third Annual RF Design Awards Contest.

Traditionally, the problem of adjusting the phase of an RF circuit has been approached with variable length lines often resembling a trombone slide. Engineers have also been known to vary phase by cutting many lengths of coaxial cable and substituting until the desired phase is obtained. This approach is tedious to say the least and does not allow the phase to be controlled dynamically. A new approach to this problem uses varactor diodes to provide continuously variable phase control.

The ideal voltage-controlled phase shift

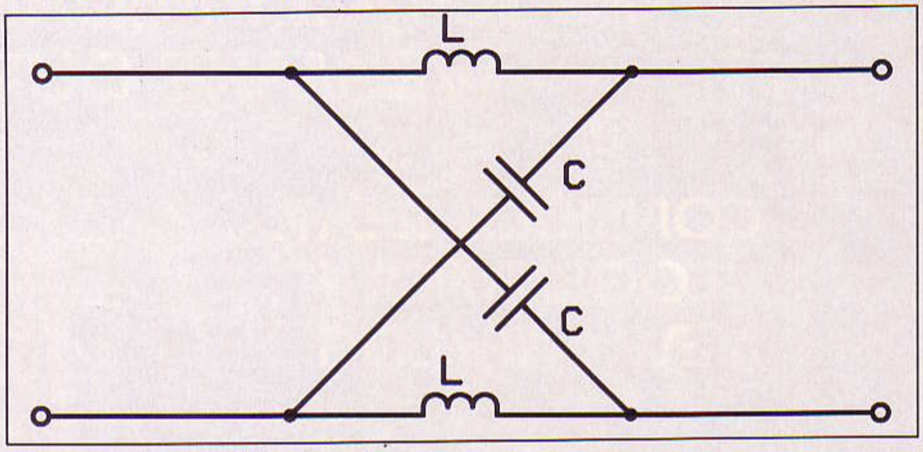

Figure 1. Phase shift network.

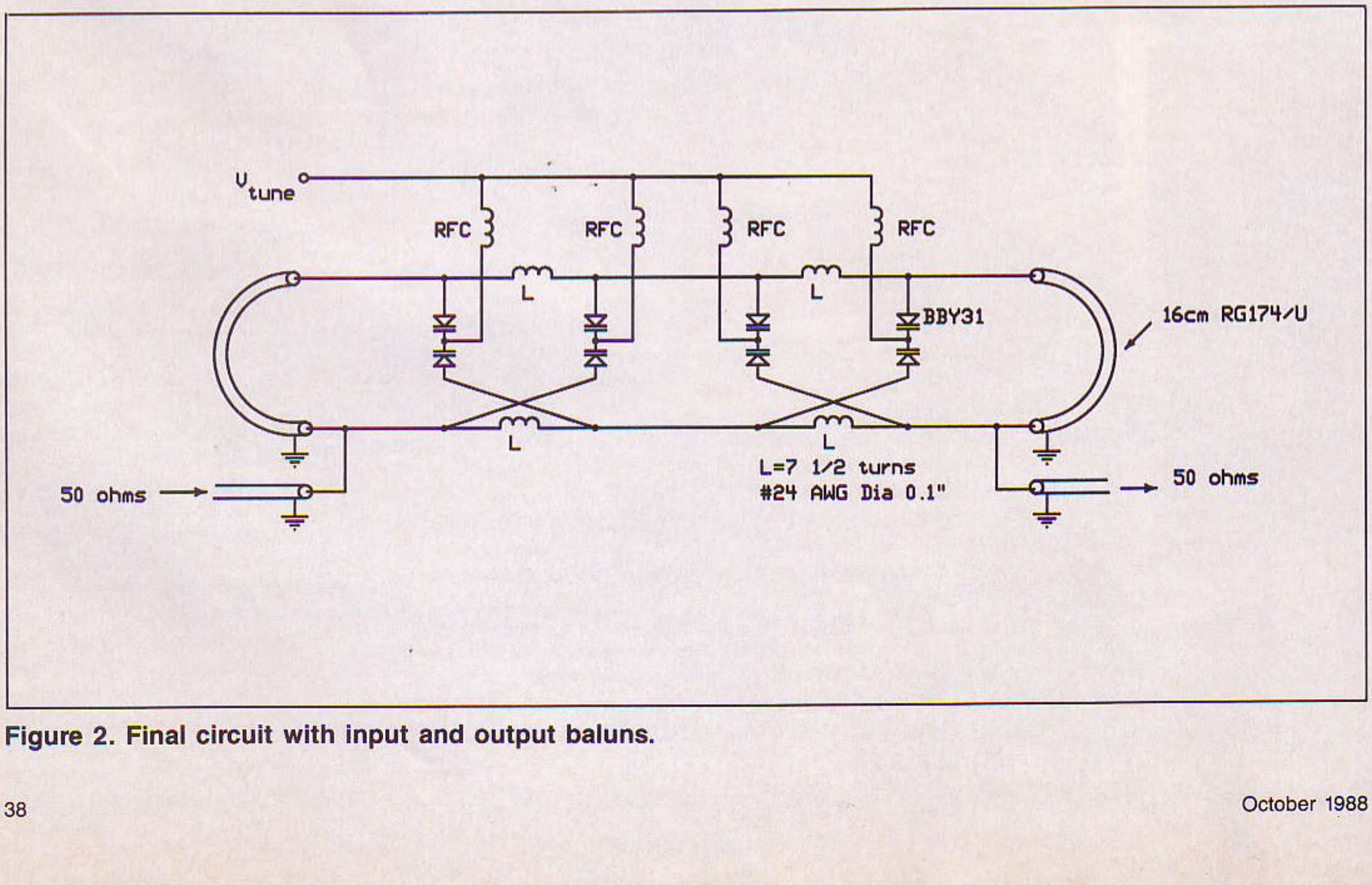

Figure 2. Final circuit with input and output baluns.

(VCPS) would have several desirable characteristics. Obviously, these would include a wide range of phase control, minimal variation of insertion loss with control voltage, and a flat magnitude response. The range of phase control is, in part, determined by the selection of the tuning diodes. Varactor selection is not critical. However, for a wide range of phase control, the varactor's capacitance should be in the range given by equation 1.

$$C \approx \frac{1}{(R\omega)} \qquad (1)$$

Substituting R = 200 ohms and $\omega = 2\pi$ (500 MHz) into equation 1 indicates that C should be in the range of 1.6 pF. In this design, the BBY31 will be used. These diodes will typically provide 8 pF at 6 volts and since two are used in series the capacitance will be 4 pF. In addition, these diodes have about a 4:1 capacitance ratio over the 2 to 12 volt range. This should result in a wide range of phase control.

To insure a flat magnitude transfer characteristic, the phase shift network shown in Figure 1 was chosen. This network is also known as an all-pass filter or delay equalizer. Since this is a balanced circuit, baluns were included on the input and output of the final design (Figure 2). Transmission line baluns were chosen because they are easily realizable at UHF frequencies. For lower frequency designs, a transformer balun could be substituted for wider bandwidth and reduced size while the transmission line baluns should be one half wavelength at the VCPS center frequency. For RG174/U the velocity of propagation is about 200×10^6 m/s. The balun length is found with equation 2.

$$l = \frac{(200 \times 10^6)}{(2f)} \qquad (2)$$

At 500 MHz, l is 20 cm. The actual circuit operated over the desired range of 450 to 550 MHz when this balun was trimmed to 16 cm. The 4 coils shown in Figure 2 are all the same value and were calculated with equations 3 and 4.

$$\alpha_o = \frac{1}{RC} \qquad (3)$$

$$L = \frac{R}{\alpha_o} \qquad (4)$$

The value for C is assumed to be fixed and is the geometric mean of the range

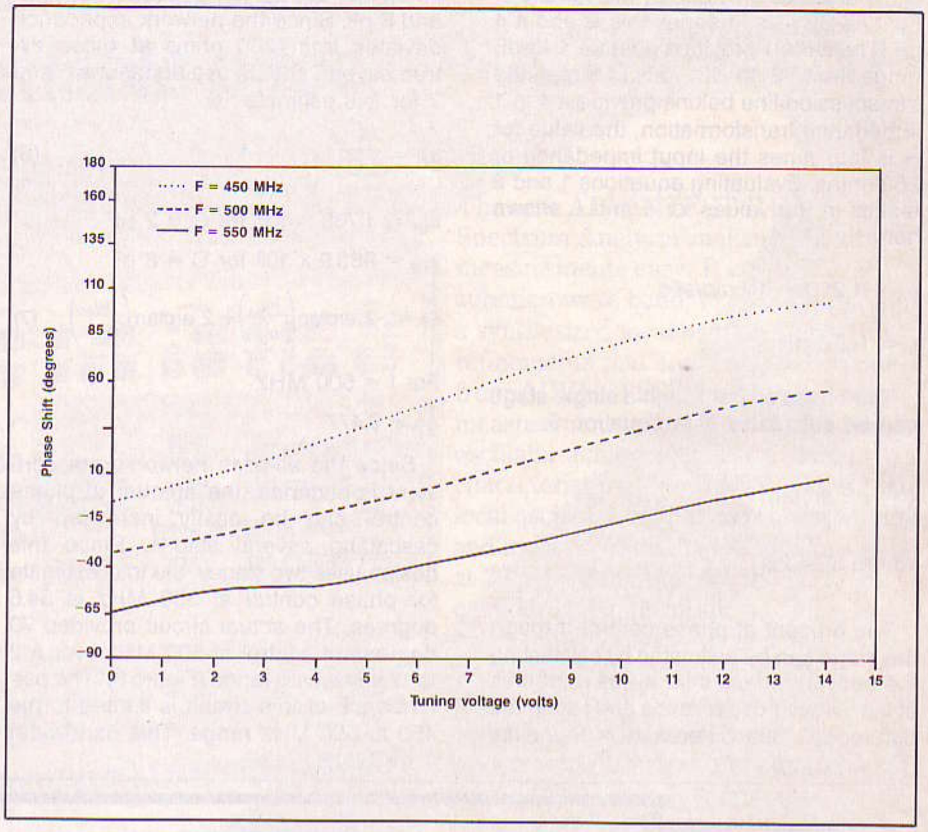

Figure 3. Voltage-controlled delay.

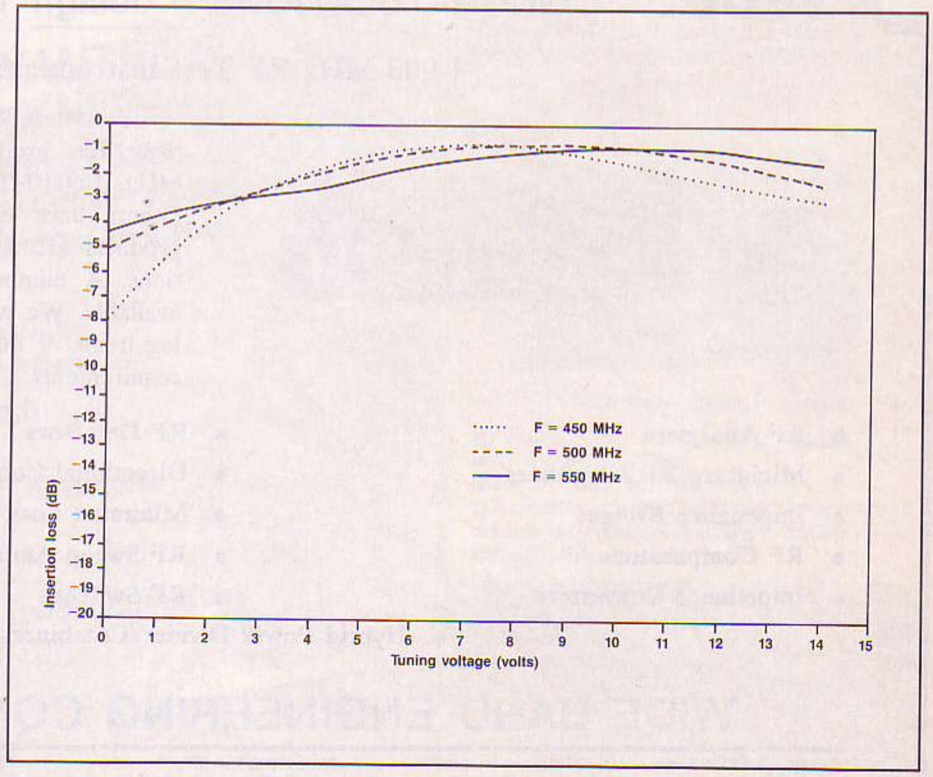

Figure 4. VCD insertion loss.

of capacitance provided by the varactors. For two BBY31s in series this is about 4 pF (The BBY31 provides about a 4-16 pF range from 2 to 12 volts.). Since the transmission line baluns provide a 4 to 1 impedance transformation, the value for R is four times the input impedance or 200 ohms. Evaluating equations 1 and 2 results in the values for α and L shown here.

$$\alpha_o = 1.250 \times 10^9 \text{ rad/sec}$$

$$L = 160.0 \text{ nH}$$

The phase shift through a single stage can be calculated with equation 5.

$$\phi = -2 \arctan\left(\frac{\omega}{\alpha_o}\right)$$

where $\omega = 2\pi f$

The amount of phase control through this stage can be estimated by calculating the network phase shift at the extremes of the varactor capacitance and taking the difference. This difference is found by finding α_o at varactor capacitances of 2 and 8 pF. Since the network impedance deviates from 200 ohms at these extremes, one should use equations 6 and 7 for this estimate.

$$\alpha_o = \frac{1}{LC} \qquad (6)$$

$$\alpha_{01} = 1.768 \times 10^9 \text{ for } C = 2 \text{ pF}$$

$$\alpha_{02} = 883.9 \times 10^9 \text{ for } C = 8 \text{ pF}$$

$$\Delta\phi = -2 \arctan\left(\frac{\omega}{\alpha_{01}}\right) + 2 \arctan\left(\frac{\omega}{\alpha_{02}}\right) \qquad (7)$$

For f = 500 MHz
$\Delta\phi = 0.477$

Since the all-pass networks are constant impedance, the amount of phase control can be easily increased by cascading several stages. Since this design uses two stages, the total estimate for phase control at 500 MHz is 54.6 degrees. The actual circuit provided 70 degrees of control at 500 MHz over a 2 to 12 volt tuning range (Figure 3). The performance of this circuit is limited to the 450 to 550 MHz range. This bandwidth restriction is due primarily to the limited bandwidth of the transmission line baluns and could no doubt be improved with lumped baluns.

Insertion loss is shown in Figure 4. As long as low varactor voltages are avoided, this loss is less than 3 dB. More important than the absolute insertion loss is the variation of loss versus tuning voltage. Figure 4 shows that, for the 2 to 12 volt range, this variation is less then ±1.0 dB. rf

References

1. Arthur B. Williams, *Electronic Filter Design Handbook,* McGraw-Hill, New York, 1981.
2. R. G. Brown, R. A. Sharpe, W. L. Hughes, R. E. Post, *Lines, Waves, and Antennas,* John Wiley & Sons, New York, 1973.

About the Author

Thomas L. Mathews is senior associate engineer at Wavetek RF Products, Inc., 5808 Churchman By-Pass, Indianapolis, IN 46203-6109. Tel: (317) 788-9351.