360-degree Linear Analog Phase Shifter Design Using Tunable Short-circuit Terminated Combline Filters

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***Abstract* — A new design technique is introduced for designing a 360-degree linear analog phase shifter at 5.2GHz. Using tunable short-circuit terminated combline (STCL) filters as reactive loads, the circuit gives a very small insertion loss (less than 1.5 dB) and an almost linear phase shift over the filter bandwidth for the full 360-degree range.**

I. Introduction

Analog and digital phase shifters each have certain advantages: the digital device offers accuracy for any bit, but requires a multiplicity of devices and considerable circuit area to combine enough bits to achieve large phase shift adjustment range. Thus, size, insertion loss, control complexity, and power consumption are significant disadvantages of the digital technique. The analog phase shifter uses less area and can achieve large amounts of phase shift with less insertion loss, at the cost of less accuracy and potential temperature sensitivity. The new technique proposed herein increases the available phase shift range, reduces the insertion loss and provides for easy temperature compensation [1] through the use of a well-known combline structure in a reflection configuration to provide phase shift based on the reflection phase characteristics of the combline network. Analog phase shifters typically employ matched pairs of tunable L-C series resonant networks in conjunction with 90-degree hybrid couplers, to achieve variable phase shift [2][3]. The signal reflected from the identical diode terminations add up at the isolated port and cancel out at the input port. The performance depends on the isolation, diode termination, coupling balance, etc.. At low frequencies, 180-degree phase shift can be achieved if more than one L-C network is employed at each hybrid port, while 180-degree phase shift is asymptotically approached with single L-C sections. When more phase shift is desired, several identical stages can be cascaded. The available phase shift range for this class of network depends on the capacitance range of the varactor diode, as well as the choice of inductance. To achieve more linear phase shift (vs. frequency) the use of an impedance matching network in front of the varactor diode is more effective than using L-C series resonant networks [4]. From a filter point of view these reactive loads can be as synthesized as lowpass filters.

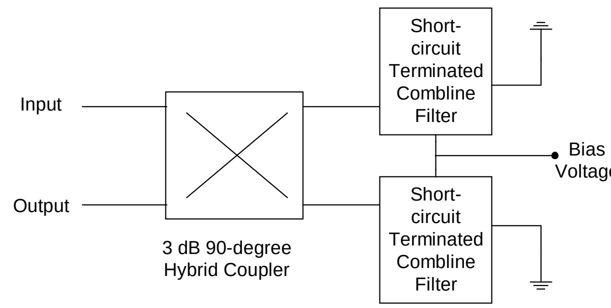

Fig. 1 Phase Shifter with the tunable short terminated combline filters as reactive loads

However, it is difficult to extend this approach to higher frequencies due to the low capacitance required for the varactor diode. As frequency increases, the capacitance of the varactor must be smaller to operate in the same impedance range. The available phase shift range thus decreases for higher frequencies, using the conventional L-C approach. As will be discussed, the L-C approach also provides only a limited linear phase shift range. In this paper, tunable short-circuit terminated combline (STCL) filters are used as matched reactive loads (Fig.1). When the output port of the filter is shorted, the reflection phase is approximately two times the insertion phase, due to the double transit of energy through the filter. The usage of the second-order STCL filters effectively doubles the linear reflection phase range of the tunable filter. The achieved phase shift range is thus wider than that achieved with a single section L-C series resonant reactive load or with a similar matching network load and varactor diode. In this paper, 360-degree linear phase shift was achieved at 5.2 GHz with a small tuning capacitance range (0.5 pF ~ 1.0 pF) and without cascaded couplers or sections. This design method can be applied at lower or higher frequencies. Design details and measured data will be presented for the

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tunable short-circuit terminated combline filters used to implement the phase shifter.

II. COMPARISON OF TUNABLE SHORT-TERMINATED COMBLINE FILTERS WITH CONVENTIONAL L-C SECTION APPROACH

Using L-C sections**,** the reflective circuit must be suitably designed to achieve the desired phase shift range, while maintaining as low an insertion loss as possible with voltage tuning. Fig.2 shows the response of several types of reactive loads. As the frequency increases, the varactor range must be smaller in order to get the same impedance range. In the case of higher frequency it is difficult to get a wide phase shift range, because the required minimum capacitance of the varactor diode is too small. Thus, it is difficult to achieve the necessary capacitance variation. Instead of a single section L-C resonant load (Fig. 2-a) or

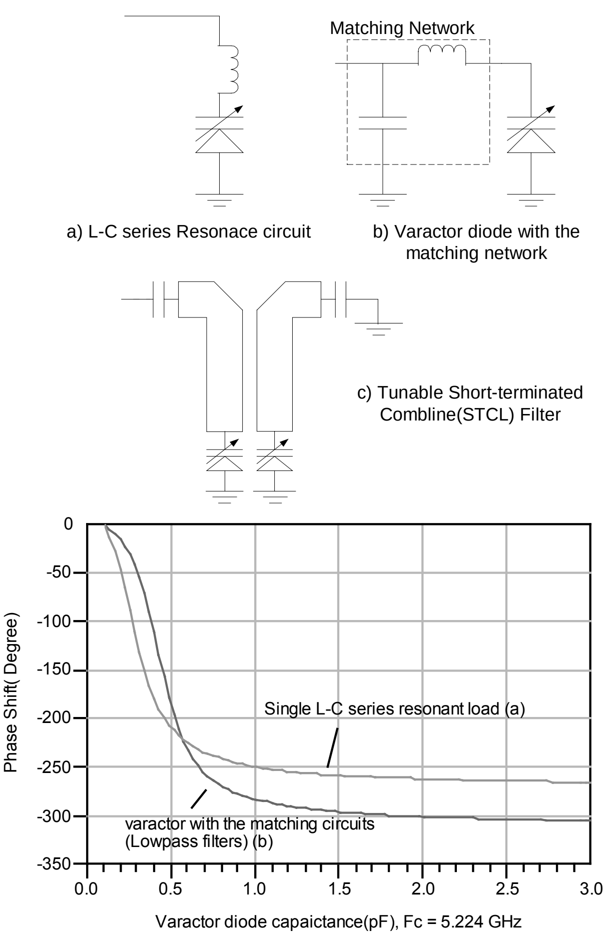

Fig. 2 Phase shift range of the reactive loads of a single L-C series resonant network(a) and low a pass type matching network(b) with the varactor diode capacitance (0.1 pF ~ 3 pF).

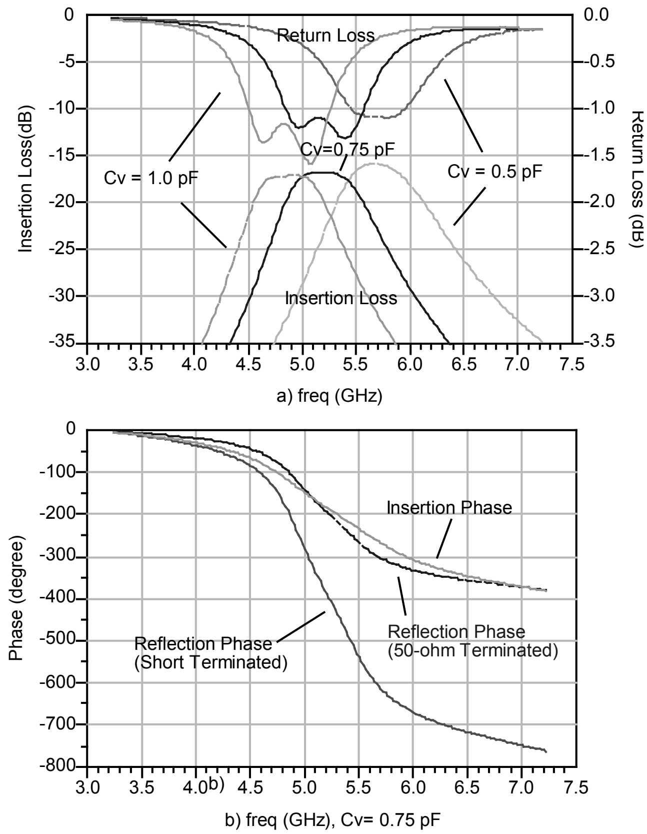

Fig. 3 Insertion, return loss and phase response of the tunable short-terminated filter.

low pass type (Fig. 2-b), multiple higher order reactive loads can be used to get a wider phase shift range for higher frequency. In this case each varactor will require different capacitance ranges.

A microstrip combline topology can be used to produce a filter with an enhanced tuning range and compact size. The configuration of the proposed short circuit terminated combline filter (STCL) is shown in Fig.2-c. The STCL filters are connected to the 0-degree and 90-degree ports of the branch-line coupler, respectively**.** Other quadrature couplers, including Lange, lumped, and broadside-coupled lines can be used instead of the branch line coupler. However, the branch-line design is convenient for low-cost, planar implementation.

A 2nd order STCL filter has a wider band linear transfer phase and reflection phase response over the pass band region, than does a two-element L-C section network, because the STCL filter order is effectively double that of L-C. When the output port of the filter is short terminated, the phase shift of reflected signal is almost twice the insertion phase (Fig. 3). To actually see the response of the STCL filter, the filter is simulated with a terminating resistance of slightly greater than zero ohms. This allows for viewing the shape of the loss curve, which otherwise would be flatter. Fig. 3 shows the insertion and return loss for the coupled line pair, terminated with 0.2 ohms, with effective unloaded Q value of 250 for the filter.

The phase change for the phase shifter results from the changes in the reflection phase response of the filter. The filter is tunable, and so for any input frequency, displays a variable phase shift, due to motion along the phase response curve. Using this reflection phase, 360-degrees of linear phase shift can be achieved. For filter implementation a coupled parallel line pair with two identical varactors was employed (Fig.2-c). Fig.3a shows the insertion and return loss of the tunable short-terminated filter. Using 0.5pF capacitance range, 1GHz-tuning range was achieved, adequate for achieving 360-degrees of phase shift to any frequency in a 5.1 to 5.3 GHz band.

The goal is to use the linear phase response region to get a 360-degree phase shift without the use of cascaded couplers. The advantage of an STCL filter is the 360-degree linear phase shift without cascading couplers. In this design we used the M/A COM GaAs Constant Gamma tuning varactor diodes (MA46H200-1056) such that the capacitance at -2 volts is 1pF with capacitance ratio 3:1(C_{T-2}/C_{T-20}) and Q=3000 at f=50 MHz, V=-4V.

$$\text{Output magnitude} \cong \tfrac{1}{2}\,(\Gamma_2 + \Gamma_1) \qquad (1)$$

where Γ_2 and Γ_1 are the reflection coefficients of the two STCL filters ($|\Gamma|e^{j\phi}$)

Equation (1) shows a relationship between the output magnitude of the phase shifter and two reactive loads. If the two reactive loads are not identical the insertion loss will increase. Fig.4 shows the output magnitude of the phase shifter vs. the difference of two reactive loads. When two reactive loads are perfectly matched most of the energy is added up at the isolated port of the coupler. To evaluate the effects of unmatched diodes, Fig.4 shows how two different varactors affect the overall insertion loss of the phase shifter. The diode mismatch causes some of the reflected energy to destructively interfere at the output port, resulting in amplitude ripple.

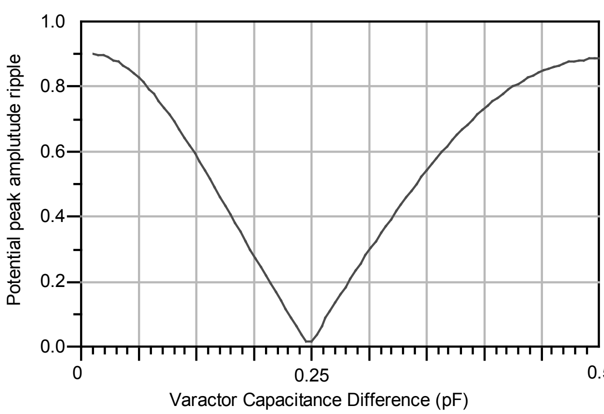

Fig. 4 A potential peak amplitude ripple vs. difference of varactor diodes.(Fc=5.224 GHz)

III. RESULT

We simulated the phase shifter with HP Advanced Design System (ADS)[6]. The coupled line pair was synthesized using Filpro [7]. Fig.5 shows the phase shift angle vs. varactor diode capacitance. Over the 100MHz bandwidth the overall phase shift shows the same phase shift response shape: linear, as was required. Fig.6 shows the insertion loss and return loss of the phase shifter. The insertion loss is less than 1.5 dB and the return loss is less than 20 dB. Fig.7 shows the Smith chart of the reflection characteristics resulting from changing the varactor diode

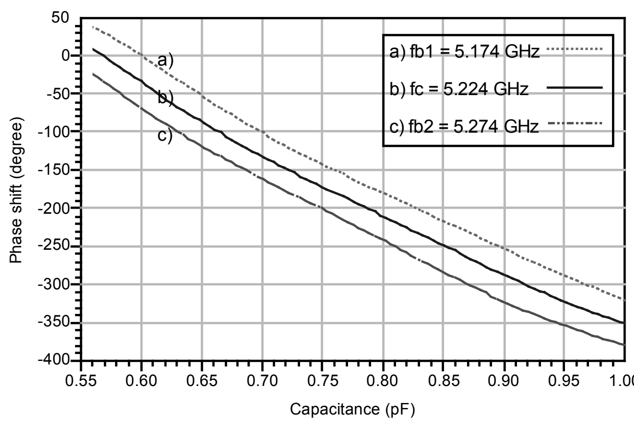

Fig. 5 Phase shift angles vs. varactor diode capacitance over 100MHz bandwidth, Fc = 5.224 GHz

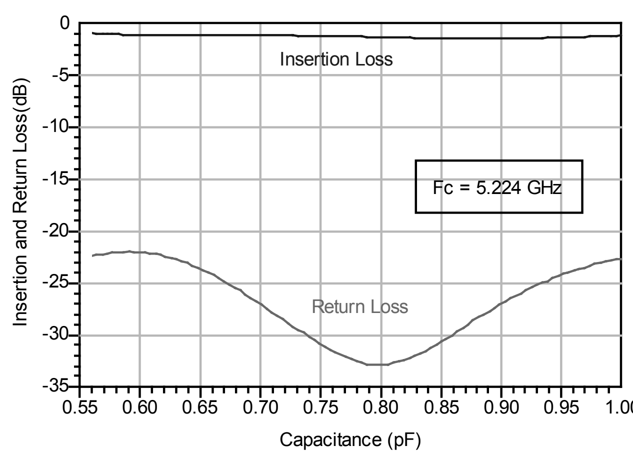

Fig. 6 Insertion and Return loss of the phase shifter

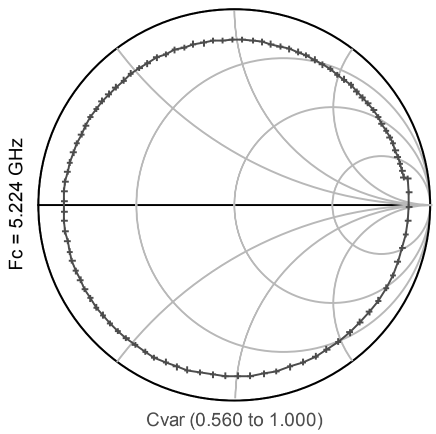

Fig. 7 Smith Chart of the reflection characteristics resulting from changing the varactor diode capacitance. (0.56 pF ~ 1.0 pF, Fc = 5.224 GHz).

capacitance, at 5.224 GHz. The Smith chart illustrates that the very high reflection coefficient is maintained during varactor capacitance change, and thus low insertion loss is possible over the entire range of the phase shifter. The reactive load circle is very close to the purely constant reactive load circle. Fig.8 and Fig.9 show the preliminary measured data of the phase shifter at Fc = 5 GHz, BW = 100 MHz. Fig.8 can be compared to Fig.4. Fig. 8 shows the experimental amplitude ripple well within the limits illustrated in Fig.4.

IV. CONCLUSIONS

The use of tunable short-terminated combline filters as matched reactive loads on a 90-degree hybrid coupler has been shown to provide double the insertion phase of each filter. Because the use of circuit volume is more efficient with resonated coupled line sections than with single L-C sections (due to filter order doubling), the overall insertion loss is lower and phase shift range greater, than with the conventional L-C approaches. A second-order combline pair has been shown to asymptotically approach 360-degree total phase shift, with a large linear range and an insertion loss of less than 1.5 dB over the full phase shift range. Extension to higher order combline or other coupled line networks should easily extend the phase shift range well beyond 360 degrees, and combline structures are practical at both higher and lower frequencies. Incorporation of active devices other than conventional varactors is also possible, and might lead to efficient implementation of other system functions. This will be explored in future work.

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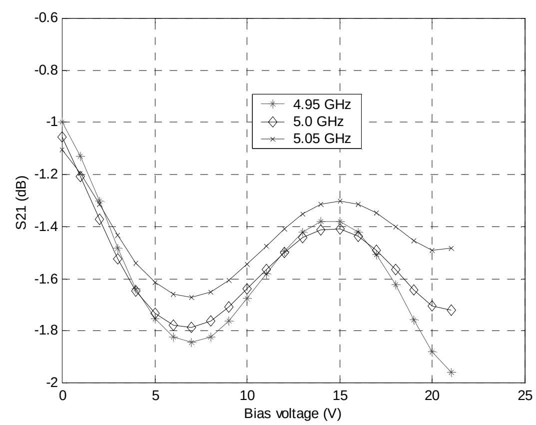

Fig.8 Measured amplitude response of the phase shifter

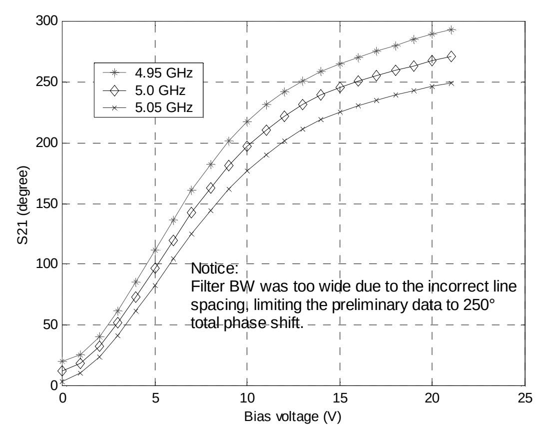

Fig. 9 Measured phase response of the phase shifter