A New Low Cost Phase Shifter for Land Mobile Satellite Transceiver

P. Mousavi(1), I. Ehtezazi(1), S. Safavi-Naeini (2), and M. Kahrizi (1)
(2)University of Waterloo, Waterloo, Ontario, Canada
(1)Intelwaves Technologies, Waterloo, Ontario, Canada
(pmousavi@intelwaves.com)

Introduction

This paper describes the design of a new low cost analog single stage phase shifter for affordable phased array antennas for mass-market land mobile satellite transceiver. A linear phase shift of more than 360-degree in Ku (12.2-12.7 GHz) band with less than 4.0 dB insertion loss is achieved. The phase shifter is composed of 3-dB hybrid coupler, novel compact reflective terminating loads and hyperabrupt junction Varactor diodes. The effect of insertion loss variation of this phase shifter over noise figure of cascaded LNA is also studied and measured.

System Requirements

The challenges in the phase shifter design for low cost mobile satellite phase array antennas are as follow: 1) Achieving phase linearity at Ku band is complicated for MIC implementation, where the required minimum Varactor capacitance becomes comparable to parasitic capacitance, 2) The circuit layout should avoid infinitesimal critical dimension to achieve high yield and reduce the manufacturing cost, and 3) Minimum control complexity with very few number of control voltages to reduce the number of digital/analog converters (DAC) .

Both analog and digital phase shifters have been proposed for these applications. While digital phase shifters offer higher precision for individual bit, it suffers from multiplicity of the switches and considerable circuit area for providing enough bits to obtain large phase shift with sufficient resolution. In addition, considerable insertion loss, control complexity and power consumption make it less attractive for low cost high volume applications.

On the other hand, analog phase shifters need less area, low power consumption and better insertion loss. Also it requires fewer active elements compared to digital phase shifters. Analog phase shifters typically employ matched pairs of tunable LC series resonators networks in conjunction with 3dB-90° hybrids couplers to achieve variable phase shift.[1,2]

Principal of Operation

Fig.1 shows the circuit topology of the reflective-type phase shifter (RTPS) consisting of a 3-dB 90-degree Hybrid coupler and low loss reflective load connected to its through and coupled ports while the other ports are symmetrically

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matched to 50 Ω input and output. The phase of RTPS can be controlled by changing the impedance of reflecting load. This can be done by varying the capacitance C_v between C_{min} and C_{max}. The absolute value of this phase variation is given by

$$\Delta\varphi = 2\left|\arctan(Z_{\max}/Z_o) - \arctan(Z_{\min}/Z_o)\right| \qquad (1)$$

The phase shift introduced by a Varactor alone is limited [1]. The phase control range can be increased by resonating the Varactor with a series inductor at their resonance frequency. However, at Ku band the required minimum amount of Varactor capacitance to produce the phase shift in excess of 180° is less than 50 fF, which is of the same order as the package and connection parasitic capacitances for MIC implementation (Fig. 2). These parasitics have dramatic effects on the phase shift linearity and may result in flattening of the C-V and consequently on the termination reactance characteristics respectively.
To solve this problem, an impedance transformer network is added to L-C series resonance networks as shown in Fig. 1. This network transforms the load impedance (Z_{LC}) to a larger value according to this equation

$$Z_p = Q^2 Z_{LC} \qquad (2)$$

where, Q is the quality factor of the network. This network increases the minimum required Varactor capacitance to 135 fF, well above those aforementioned parasitic capacitances. Also, as shown in Fig. 2, it reduces the required Varactor tuning range. Another effect of this network is to decrease the variation of magnitude and as a result reducing the loss variation of the phase shifter.

Phase Shifter Design and Measurement

A single stage phase shifter was designed at the center frequency of 12.5 GHz. In this design we used commercially available GaAs hyperabrupt junction Varactor diodes with constant Gamma of 1.25 and series resistance of R_s = 3.5 Ω. The capacitance variation is from 1.0 pF to 0.10 pF for the DC voltage of 0 to 12 volts respectively. The operating temperature range is from -50°C to 150° C which is ideal for land mobile satellite links.
Two stage reflective loads shown in Fig. 1, are used to maximized insertion phase and minimized insertion loss variation. The load inductors, L_S, are fabricated using via to ground with the diameter of 0.8 mm. The values of the inductors are 0.24 nH. The impedance transformer networks (reflective loads) are designed using stepped microstrip line. The phase shifter simulation was performed using Agilent Advanced Designed System (ADS).
Fig. 3 shows a fabricated single stage phase shifter. It was tested using network analyzer (HP 8722ES). Fig. 4 shows the measured phase shift for this device. The phase shift of 376 degree was obtained over the range of frequency of 12.0 to 13.0 GHz by changing voltage from 2 to 10 volts which is corresponding to the

capacitance variation between 0.47 to 0.13 pF respectively. The phase shift variation over the operating frequency is only 10-degree. Compared with measurement results of [2] it has four times lager bandwidth and less phase shift variation over the band of operation with only 8 volt voltage variation. The latter is important for the operation on a vehicle.

Fig. 5 illustrates the measured insertion loss. In the measurement and simulation the effect of SMA connectors and DC block capacitors are also included. By subtracting these losses (~1dB) the total insertion loss of the circuits becomes $-3.2 \pm 0.8\,\mathrm{dB}$ (for 12.2 to 12.7 GHz). Fig. 6 demonstrates the measured return loss, which is better than -10dB in the whole range of frequency (12.2 to 12.7 GHz). In this configuration, the bandwidth of the phase shifter in terms of return loss and insertion loss, are mostly dominated by 3-dB hybrid coupler. The bandwidth will be improved by using Lange coupler.

The phase shifter was tested against temperature range of -40°C to 80°C which shows the phase variation of less than 6 degrees.

One of the governing factors in designing phased array antennas for land mobile satellite communication is G/T. The difference of insertion loss among channels in this kind of system may disturb the overall G/T of the system. Therefore, the NF of cascaded LNA and the phase shifter is measured for different voltages. The original NF of LNA is less than 1 dB over the band of operation with the gain of 22 dB. By changing the voltage the overall NF of the channel varies only by 0.1 dB. (Fig. 7) This will cause less than ± 0.1 dB variation on the G/T of the system.

Conclusion

A novel low cost MIC analog phase shifter at Ku band was introduced in this paper. The proposed structure is suitable for low profile low cost phased array antennas for land mobile satellite systems. The phase shifter incorporated novel impedance transformer network to reduce the effect of parasitic on resonated load (LC) and to minimize the required Varactor tuning range. The phase shifter showed minimum sensitivity towards the fabrication errors.

ACKNOWLEDGMENTS

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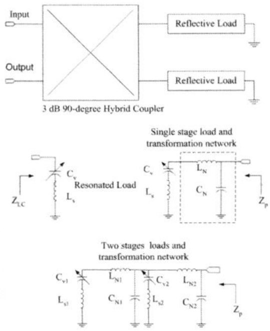

Fig. 1: Phase shifter topology of RTPS with different reflective loads

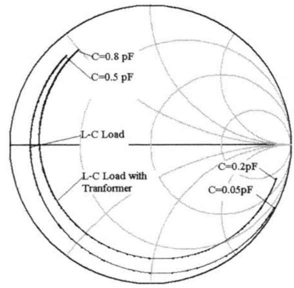

Fig. 2: Phase shift for reflective LC load and LC with impedance transformer

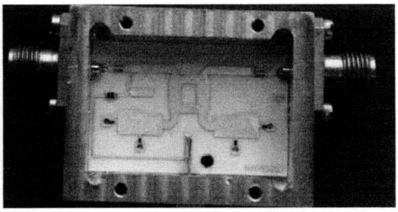

Fig. 3: Fabricated single stage phase shifter

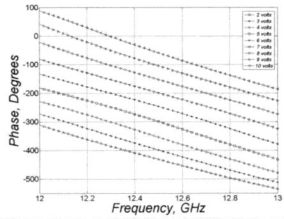

Fig. 4: Measured phase shift for single stage phase shifter

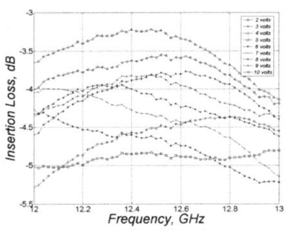

Fig. 5: Measured insertion loss

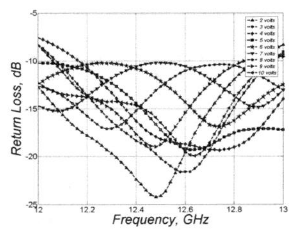

Fig. 6: Measured return loss

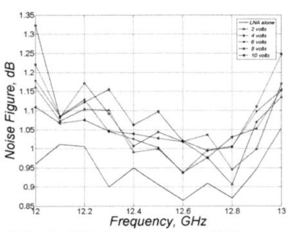

Fig. 7: Measured noise figure variation of the phase shifter and the cascaded LNA