Improved 60GHz Loaded-Line Phase Shifter Using Tunable Inductor

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***Abstract*—In this paper we propose a modified varactor loaded π-cell phase shifter to increase the phase shift range per cell and to minimize the input/output return losses over a large frequency band. A tunable transformer-based inductor is employed instead of the fixed inductor in conventional π-cell to keep the characteristic impedance of the line independent of the phase shift. In the proposed transformer based tunable inductor secondary terminals of the transformer are connected to a varactor to produce a variable inductor at the input of the transformer. To verify the operation principle, a 60GHz transformer in 65nm CMOS technology is EM simulated in HFSS and results have been imported into the circuit simulator for the overall characterization of the system with a varactor. A large phase shift of 48^0, average insertion loss of 3.5dB and input/output return loss of 10dB is achieved in the 60 GHz band.**

***Keywords*—phase shifter, varactor, 65nm CMOS**

I. INTRODUCTION

The unlicensed 60-GHz ISM band is targeted for development of high-data-rate wireless communication channels for multi-Gbps wireless network applications as it offers a large 7 GHz bandwidth [1]. However, employing beamforming by phased arrays is inevitable due to higher path loss at these frequencies [2]. Since CMOS phase shifters play main role in the phased array systems, their cost is a driving factor in commercial system designs which is mostly determined by the chip area [3]. Even varactor-loaded lines are continues adjustable phase shifters with simple control units, their application is limited in low cost commercial phased array due to their large area consumed by large number of cells [4]. Here, a novel structure was proposed to enhance the performance of unit cells by increasing its phase shift range in conventional loaded-line phase shifter. Therefore less number of cells is required in the phase shifter structure resulting in smaller chip area.

II. ANALYSIS AND DESIGN

Fig. 1.a shows a conventional π-cell varactor loaded phase shifter. An artificial transmission line can be constructed by cascading several π-cells. The time delay or phase shift of the transmission line can be varied by changing the capacitance of the varactors. However, as the characteristic impedance of the line is related to varactor capacitance, the characteristic impedance of the line shifts with the phase causing large return losses for portion of the phase range.

Fig. 1.b shows the modified π-cell loaded line phase shifter which replaced fix inductor by a tunable inductor (TID). The proposed structure enables tuning values of L_{in} and C_p simultaneously to preserve the characteristic impedance of line. In addition, the proposed structure produces approximately twice the phase shift as in the conventional LC phase shifter. Table 1 compares the proposed modified π-cell with the conventional one and confirms how adding another degree of freedom enables a phase shifter to cover more phase shift range while meeting the same reflection loss and characteristic impedance requirements.

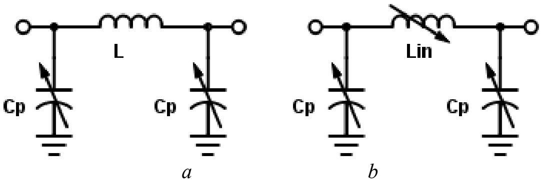

Fig. 1 (a) Conventional and (b) proposed π-cell varactor loaded

TABLE 1 THEORETICAL COMPARISON BETWEEN CONVENTIONAL AND PROPOSED Π-CELL

	Traditional Cell	**Proposed Cell**
C_{pmax}	$C_{pmin}.x$	$C_{pmin}.x$
L_{max}	L_{min}	$L_{in,min}.x$
Phase shift	$\sqrt{L.x.C_{pmin}}$	$x.\sqrt{L_{in,min}.C_{pmin}}$
max $phase(\theta_{max})$	$\theta_{min}.\sqrt{x}$	$\theta_{min}.x$
Cell Impedance	$\sqrt{L/C_p}$	$\sqrt{L_{in}/C_p}$
$Zmax$	$\sqrt{x}$. Zmin	x. Zmin

A. *TID*

Fig. 2 illustrates the schematic of the proposed TID, consisting of a transformer with self-inductors L_p as a primary, L_s as a secondary, and a coupling factor k, and a parallel varactor C_L tuned by $V_{tune(CL)}$.

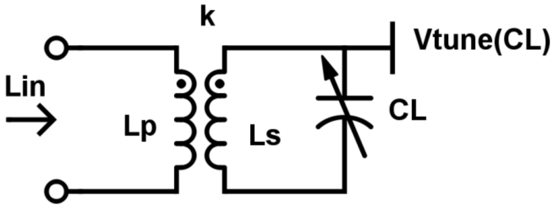

Fig. 2 Tunable inductor circuit schematic

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Solving transformer equation system, input inductance seen from primary loop terminals can be expressed as a function of self-inductors, coupling factor, frequency, and varactor C_L as

$$L_{in} = L_p\left(1+\frac{k^2\, L_s\ C_L\,\omega^2}{(1-\ L_s\ C_L\,\omega^2\ )}\right) \qquad (1)$$

$$Z_{T.L} = \sqrt{\frac{L_{in}}{C_p}},\ f_{res(min)} = \frac{1}{2\pi\sqrt{L_{in}C_p}} \qquad (2)$$

To achieve the required frequency response out of unit cell, L_s and L_p was obtained through substituting L_{in} in the π-cell and transmission line equations with (1) and (2).

Shown in Fig. 3, the layout of 1:1 stacked-up transformer with 15um radius with 8um trace width inductors is EM simulated and optimized at 60GHz. The primary and secondary loops of the transformer are designed on two top layers of 65nm CMOS substrate as they have highest thickness and less loss.

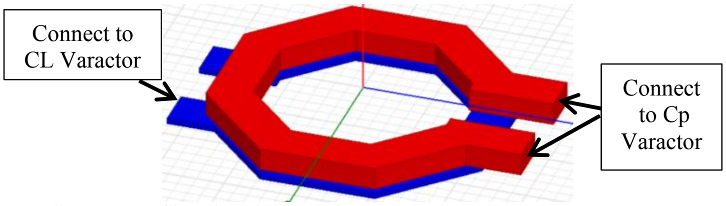

Fig. 3 60GHz flipped stacked transformer

B. *60GHz Transformer-based π-cell loaded line phase shifter*

Fig. 4 illustrates the schematic for 60GHz transformer-based π-cell loaded line phase shifter. Here, V_{tune} for TID changes its inductance from 55pH to 82pH and V_{tunep} changes line varactor capacitances.

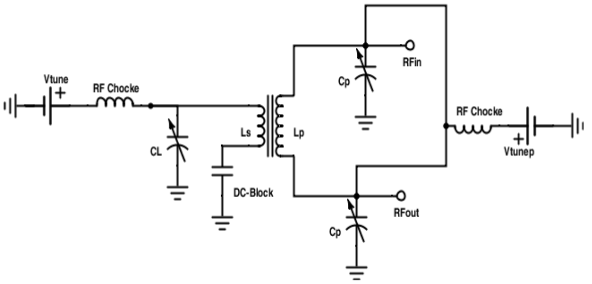

Fig. 4 Proposed π-cell schematic

C. *Simulations and Results*

The simulated phase shifter performance is illustrated in Fig. 5, Fig. 6 and Fig. 7 . The phase shift range is 48^0 in the proposed unit cell comparing to 26^0 in conventional one when reflection loss is lower than -10dB as shown in Fig. 7. In Fig. 6, 4.9dB loss variation is acceptable and can be compensated in VGAs or attenuator components which usually employed in phase arrays systems as well.

I. CONCLUSION

Here, a novel -phase shifter is proposed that changes the value of inductors and capacitors simultaneously to preserve the line characteristic impedance and achieve a larger phase shift than that can be obtained from conventional LC phase shifters. The proposed phase shifter cell achieved 48^0 phase shift over one π-cell which is almost twice the conventional π-cell. Using the proposed cell in phase shifter structures can reduce the chip area as requires smaller cell numbers for the same amount of phase shift over the line.

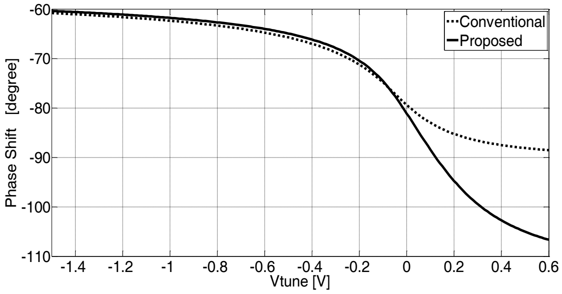

Fig. 5 Phase shift range versus V_{tune} *at 60GHz*

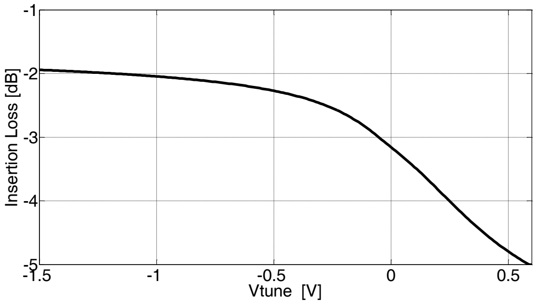

Fig. 6 Loss of phase shifter *versus* V_{tune} at 60GHz

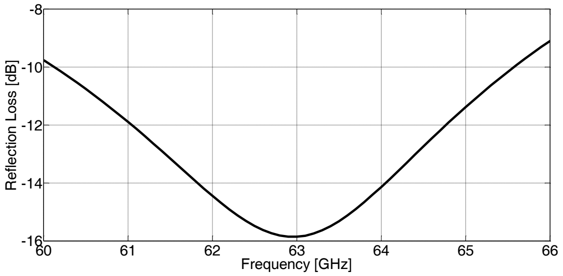

Fig. 7. Reflection Loss of proposed phase Shifter versus frequency

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