A 180° tunable analog phase shifter based on a single all-pass unit cell

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ABSTRACT: *This letter describes an analog phase shifter (PS) able to provide a continuously tunable phase shift up to 180° by using a single all-pass unit cell. The proposed topology is compact and easy to implement, and brings an interesting compromise between phase variation, insertion and return losses. Indeed, for a 7.5:1 tuning ratio of varactor capacitance, a phase shift variation of more than 186° is obtained from 6 to 7 GHz with a maximum insertion loss of 1.8 dB. The 105 °/dB resulting Figure-of-Merit (FoM) is thus among the best in distributed approaches with varactor*s.

Key words: *phase shifters; tunable phase shifter; all-pass network; phase array.*

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1. INTRODUCTION

Phase shifters (PS) have applications in various microwave radio equipment, for example in phases array antennas [1]-[2]. PS transfers the appropriate phase values to the antenna elements in order to form the main beam of electronically-scanned phased array antennas. As analog phase shifters provide a continuously variable phase shift, they are likely to meet a wide range of potential applications. Analog PS specifications are very restrictive, particularly on the phase flatness over the bandwidth and on the phase shift variation versus the active component tunability. In many cases, several stages of PS are cascaded to compensate for a restricted range of variation but at the expense of insertion loss and thus of the final Figure-of-Merit (FoM). This is particularly true for low-pass and high-pass topologies. Thus, all-pass circuits are preferably used: e.g. a conventional distributed PS implemented with a 3-dB 90° hybrid branch-line coupler [2]-[3] with two varactors or a more compact topology with a wider operating frequency range as proposed by Hayashi & al [4]. Both designs are suitable for frequency domain where lumped elements can no more be used. Compared to these previous works, the topology described in this paper reaches a new level of compactness and phase-variation range.

2. Circuit configuration

The proposed all-pass PS consists in a coupled-line section connected at one end (like a Schiffman section) and associated with two varactors C1 and C2 as depicted in Figure 1. The whole analysis of the novel topology was done by considering the even and odd mode approach to derive the phase expression as well as the matching conditions. Optimal input-output matching conditions (S_{11}dB and S_{22}dB $\rightarrow -\infty$) are obtained for a coupled-line section with a 90° electric length at the normalized frequency f_0. In that case, a simplified relation between the two varactor capacitances and the even mode impedance is obtained:

$$C_2 = 4(\frac{Z_0}{Z_{0e}})^2 C_1 \qquad (1)$$

A specific case is obtained from (1) by setting the even-mode impedance Z_{0e} = 50 Ω. Thus, it corresponds to 50 Ω uncoupled lines of 90° electrical length (i.e. the unfolded design proposed in [4]) and leads to C_2= $4C_1$ as given by synthesis relation from [4].

In the general case (quarter-wavelength coupled section), choosing an integer ratio $k=C_2/C_1$ will simplify the design with identical varactors in chip package. Setting k=2 corresponds to a medium coupling ratio with $Z_{0e} = \sqrt{2}.Z_0 = 70.7\ \Omega$, thus relaxing constrains on technological dimension and sensitivity. In these configurations, i.e. with quarter-wavelength lines at f_0 (here 10 GHz), Table 1 compares the phase variations (ΔΦ) at f_0 from respectively the conventional PS, the Hayashi's PS and the proposed PS for an identical varactor tuning range (ΔC). Results are close; however Hayashi and our PS unit cells exhibit a much wider matched frequency band.

Maximizing phase deviation is our main objective; this feature appears around $f_0/2$ (5 GHz) for these latter PSs together with an input/output matching degradation. It corresponds to an inflexion point in the phase curves and seems promising to get at least 180° phase agility at the condition that a satisfying level of S_{11} may be obtained. In this aim, a multi-criteria optimization on the coupled-line section of the proposed PS was set under ADS software. At this frequency, optimum even and odd mode impedances are found to be respectively equal to 92 Ω and 47 Ω (for k=2). The phase variation is improved up to 200° (Table 1) and the circuit remains matched over the entire varactor tuning range. On the other hand, the Hayashi unit cell becomes unmatched from 0.4 pF which limits the phase variation at 83°.

3. EXPERIMENTAL VALIDATIONS

To highlight the benefits of this topology, a proof-of-concept PS was designed for the 6-7 GHz frequency band. MA46H120 varactor from M/A-COM [5] was used; our measurements showed that its capacitance value goes from 1.15 to 0.15 pF for a control voltage varying respectively from 0 to 15 V. These values are in overall agreement with those provided by the manufacturer. The varactor measured S-parameters and EM models for the distributed microstrip sections were taken into account in the final optimization process, together with bias component influence.

Figure 2 shows a photograph of the constructed PS on an RF-35 substrate (h = 0.78mm, ε_r = 3.5, tan δ = 0.0023) and all the lumped components used. C_{DCB} are the DC blocking capacitors; resistances, R, are used to bias the varactors, C_V. Two varactors of capacitance C_V were placed in series to get $C_1 = C_V/2$, and another one was connected to the ground plane to get $C_2 = C_V$. Thus, only a single bias point is required.

Figure 3 shows the simulated and measured results of S_{11} and S_{21} magnitudes: a good agreement is obtained. Bias voltage was varied from 0 to 15 V. From the measured results, it can be seen that the circuit is well matched in a wide frequency band, which verifies it all-pass behaviour. Minimum phase error and a good insertion loss are obtained in the 6–7 GHz. In this band, the maximum insertion loss is 1.8 dB and the return loss is better than 12 dB.

In Figure 4, the comparison between the simulated and measured phase shift shows a good agreement. For just one cell, the phase shift can be tuned by more than 180° over the entire bandwidth.

The error on the phase is lower than ±8° for all over the entire voltage span. Table 2 compares the cell's characteristics with the current state-of-the-art performances of phase shifters with varactors. To our knowledge, the proposed phase shifter has the best compromise between FoM and bandwidth among the reported phase shifters.

4. CONCLUSION

In this letter, we have presented a novel topology of PS designed using distributed components and varactors. We have shown the benefits of this topology compared to similar existing approaches. The proposed PS was optimized to ensure matching for the 6-7 GHz operating frequency range and to provide a wide phase-agility range with low phase error. In this whole band, a single unit-cell PS allows a continuously tunable phase shift of more than 180° with only one control voltage. Although it is implemented in hybrid technology, the circuit is compact with a low insertion loss; thus, a two-stage PS could be implemented to get 360° phase agility.

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Figure captions

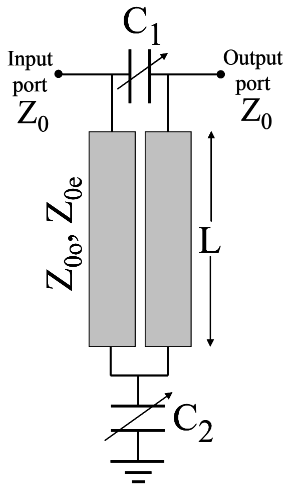

Figure 1 Proposed all-pass phase shifter topology

Table 1: Comparison of maximum phase variation ($\Delta\Phi$) and matching for a capacitance variation (ΔC) for conventional, Hayashi and proposed PSs

	Return loss (dB)	ΔC (pF)	$\Delta\Phi$ (°)
Conventional PS (90° hybrid) @f_0	perfectly matched (Narrowband)	$0.1 \rightarrow 1$	110
Hayashi PS @f_0	perfectly matched (wide band)	$0.1 \rightarrow 1$	97
Proposed PS @f_0	perfectly matched (wide band)	$0.1 \rightarrow 1$	97
Hayashi PS @$f_0/2$	< -10 (wide band)	$0.1 \rightarrow 0.4$	83
Proposed PS @$f_0/2$	< -11 (wide band)	$0.1 \rightarrow 1$	200

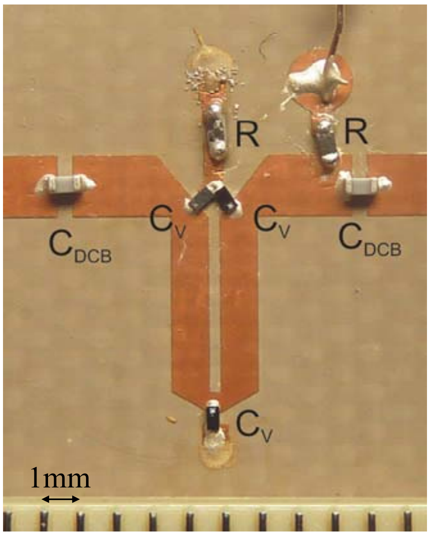

Figure 2 Phase shifter photograph. C_{DCB} = 47 pF, R = 3.3 kΩ, C_V are MA46H120 varactors, line width W=1.07 mm and slot between coupled lines, S= 0.31 mm

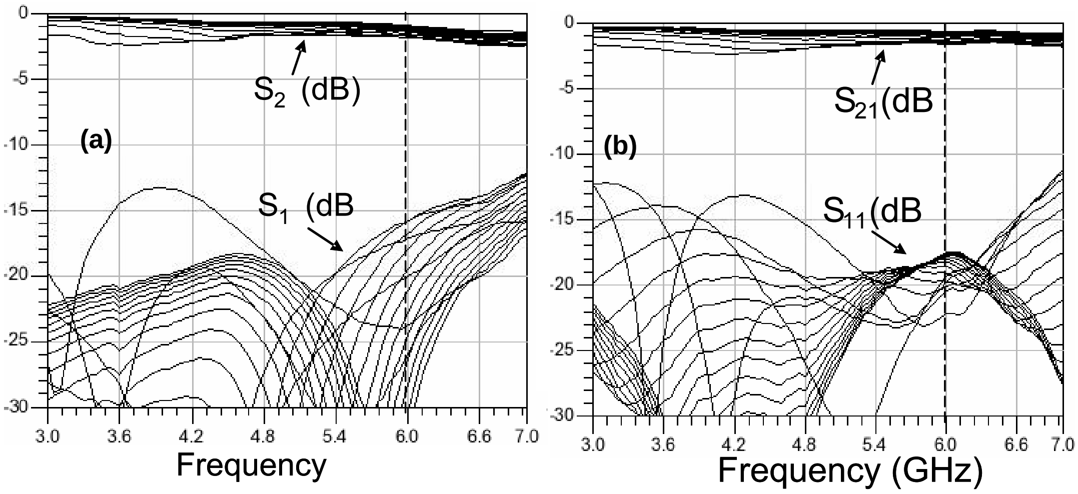

Figure 3 (a) Simulated and (b) Measured S-Parameters

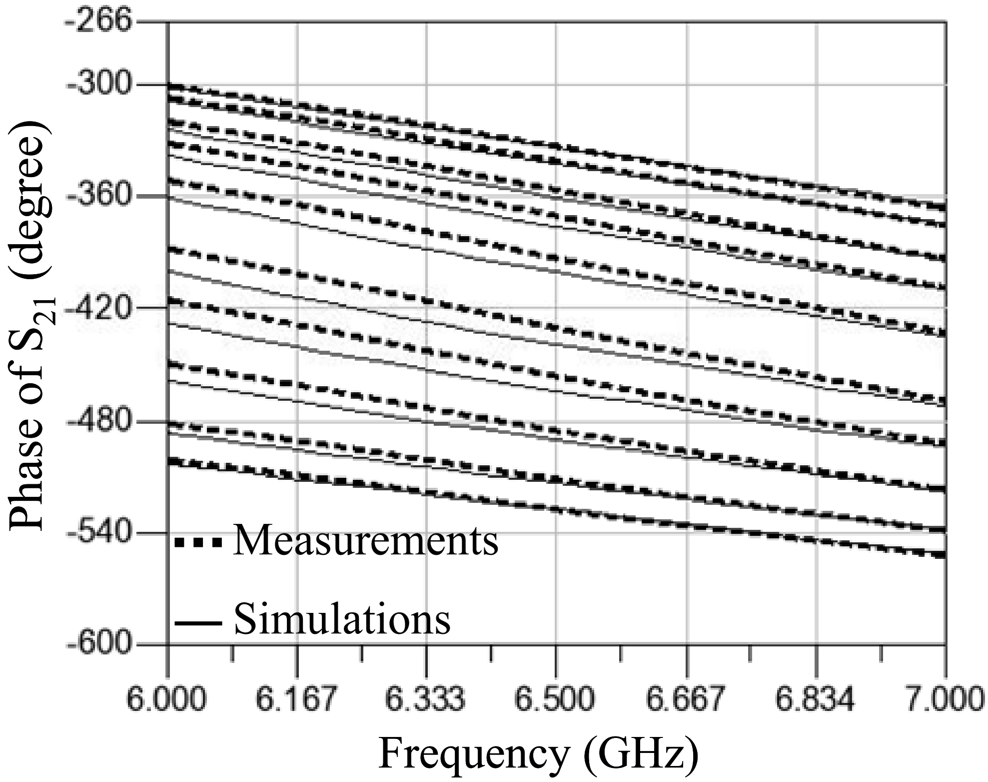

Figure 4 Simulated and Measured phase shifts

Table 2: Performance comparison of the PSs

Ref	**Phase control (°)**	**Freq. (GHz)**	**Max. Ins. Loss (dB)**	**FoM* (°/dB)**
[4]	180	12 - 14	4.7	38.2
[6]	360	5 - 6	5.7	53.7
[7]	90	4 - 6	2.2	40.9
[8]	180	4.4 - 5.6	4.5	40
[9]	210	6.1 - 6.3	6.7	31.3
[10]	360	9 - 10	8.6	41.9
[11]	360	11 - 13	7.8	46.2
[12]	230	1.9 - 2.1	1.5	153
This work	**190**	**6 - 7**	**1.8**	**105**

$$^{*}\ FoM = \frac{\Delta\varphi_{\max}}{IL_{\max}}$$