X-band Reflection-Type Phase Shifters Using Coupled Line Couplers on Single Layer RF PCB

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***Abstract*—In this paper, an X-band reflection-type phase shifter is presented. It is based on a single layer stub-loaded coupled line coupler loaded by two-varactor tuning circuits. This choice of coupler significantly improves on the phase shifter bandwidth achievable with a branch-line coupler, as it features lower phase imbalance across the band of interest. The proof-of-concept prototype achieves better than 10-dB return loss across a 20 % fractional bandwidth. The phase shifter further exhibits insertion loss of 2.1 ± 1.3 dB and maximum phase shift of 392° at 10 GHz, leading to a state-of-the-art figure of merit at X-band of 115 °/dB. The occupied area is 0.25 λ_g^2.**

***Index Terms*— reflection-type phase shifter, bandwidth, varactors, X-band.**

I. INTRODUCTION

PHASED array systems are widely used in RADAR and satellite communication, with phase shifters being an indispensable component thereof. Phase shifters should be compact, have minimal loss, low loss variation for different phase shifting states, and a wide bandwidth [1]. The Figure of Merit (FoM) with which phase shifters are evaluated is defined as [2]:

$$FoM = \frac{\Delta\varphi_{max}}{IL_{max}}, \quad (1)$$

where $\Delta\varphi_{max}$ is the maximum relative phase shift and IL_{max} is the maximum insertion loss across all phase shifting states.

A common phase shifter topology is the reflection-type phase shifter (RTPS), which comprises of a 3-dB coupler terminated with reflective loads at the through and coupled ports. Controlled reflective loads have been implemented using PIN diodes [3] with discrete control states, and varactors [2], [4-6] for continuous analogue control. In both cases the amount of relative phase shift depends on the phase change of the reflective loads. To this end, multi-varactor circuits have been implemented to increase the maximum achievable relative phase shift [6].

Branch-line and Lange couplers have been used extensively as coupling structures due to the simplicity of achieving the required 3-dB coupling value [2], [4], [7]. Branch-line couplers, however, occupy considerable board space and exhibit limited bandwidth, while Lange couplers require wirebonds or multi-layer interconnects on planar media. The aspect ratio of branch-line couplers at X-/Ku-band frequencies is also compromised, as the width of the transmission lines becomes comparable to their length. This leads to complex designs, especially for the T-junctions.

Coupled line couplers have been used to reduce the size occupied by the couplers in RTPS [3], [5]-[6], but typically require slotted ground perforations [3], SMD capacitors to increase the coupling [5], or multilayer manufacturing [6], all of which complicate manufacturing.

On the other hand, it has been shown that high directivity coupling, with low phase imbalance, can be achieved using simple single layer RF PCB microstrip coupled lines with the addition of a tightly coupled series stub placed in the center of each of the transmission line sections [8]. This concept leads to wide band and compact 3-dB couplers that can be used for RTPS designs.

It has been determined recently, in theory, that the phase imbalance of the coupler used in the design of a RTPS has a dramatic influence on the fractional bandwidth (FBW) of the RTPS [9]. In that context, this work proposes the novel combination of the coupler previously developed in [8], which has a low phase imbalance across a large bandwidth, and the reflective load circuit in [2], to implement a compact and wideband X-band RTPS in single-layer RF PCB. It results in a RTPS exhibiting an excellent trade-off between electrical performance (FoM and bandwidth) and size.

Comparative designs implementing RTPSs with branch-line and stub-loaded couplers are presented in Section II, illustrating the improvement resulting from this choice. Measurement results are shown in Section III and compared to the state-of-the-art. The paper is concluded in Section IV.

II. COMPARATIVE DESIGNS

To establish the potential improvement in using a stub-loaded coupler, two RTPSs are designed and full-wave simulated. The synthesis procedure of the stub-loaded coupled

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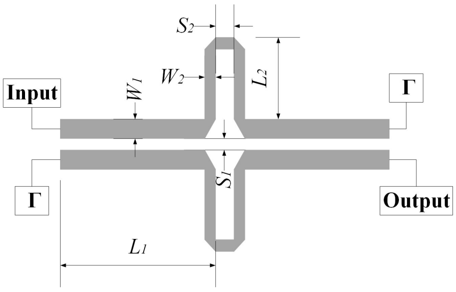

Fig. 1. Schematic representation of RTPS

TABLE I
DIMENSIONS OF STUB-LOADED COUPLED LINE COUPLER

Parameter	Value (mm)
W_1	0.69
L_1	4.58
S_1	0.15
W_2	0.41
L_2	3.41
S_2	0.19

line coupler (Fig. 1) detailed in [8] is used to determine the coupled line lengths L_1 and L_2, as well as coupling values k_1 and k_2. The full-wave optimized dimensions are given in Table I, as implemented on Rogers RO4003C substrate ($\varepsilon_r = 3.55$) of 0.813 mm thickness. The coupler is slightly over-coupled to increase the operational bandwidth of the final RTPS [7]. The coupler is loaded with a two-element ideal capacitor network [2], producing the response shown in Fig. 2, (RTPS 10-dB return loss bandwidth indicated in blue hatching). As a counter-example, a branch-line coupler was synthesized on the same substrate, and the same loading network applied to create an RTPS, producing the response also shown in Fig. 2 (RTPS 10-dB return loss bandwidth indicated in red hatching).

From this comparison, it is clear that the stub-loaded coupler has an increase of 75 % in 10-dB return loss bandwidth as compared to the branch-line coupler based RTPS; with almost comparable performance in terms of insertion loss and insertion loss variation, except below approximately 8.8 GHz where insertion loss increases for the branch-line coupler version. The origin of this improvement in bandwidth may be traced to a comparison of the phase responses of the two couplers in isolation, shown in Fig. 3. The stub-loaded coupler exhibits lower phase imbalance than the branch-line coupler (below 2°) across the band of interest, which translates into a wider operating band for the RTPS [9].

To construct the practical RTPS, the two-varactor reflective loads (Γ in Fig. 1) were synthesized using the procedure described in [2] and shown in Fig. 4, with the transmission line and radial stub added for broadband biasing. The maximum relative phase shift and minimum transmission losses are obtained when the transmission line connecting the two identical varactors has a maximum impedance (Z_{TL}) and an electrical length (Θ_{TL}) close to 45° [2]. The selected varactor is the MACOM MA46580 with a total capacitance ranging from 0.13 pF to 2.2 pF, with a parasitic series inductance of $L_s = 0.27$ nH, as well as a Q-factor larger than 3000 at 50 MHz for a reverse bias voltage (V_R) of 4 V. Taking

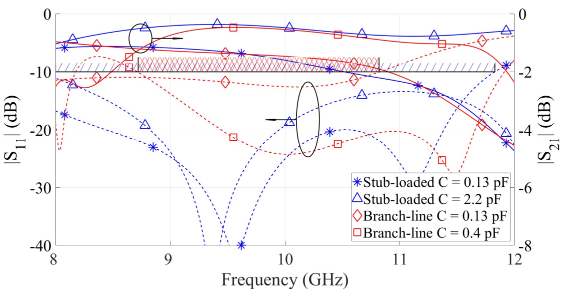

Fig. 2. Comparative S-parameters, for worst-case 10-dB return loss bandwidth, of RTPSs using branch-line and stub-loaded couplers and ideal capacitors for the reflective load networks

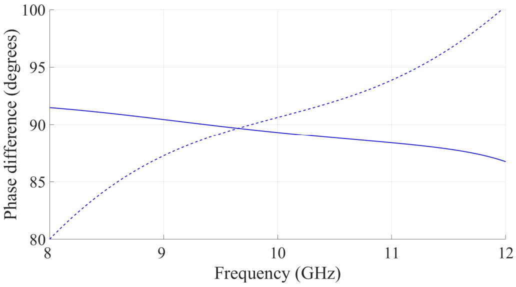

Fig. 3. Simulated phase difference between through and coupled ports of 3-dB stub-loaded coupled line coupler (solid) and branch-line coupler (dotted)

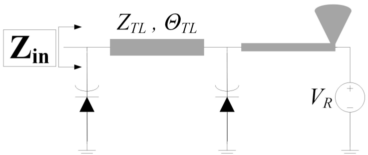

Fig. 4. Schematic view of two varactor reflective load circuit

the characteristics of the varactors into account, the reflective load layout was optimized in a full-wave solver to provide maximum reflection magnitude, achieving a maximum relative reflection phase shift of 397° at 10 GHz across the 0 V - 16 V tuning range. The optimized transmission line parameters are $Z_{TL} = 111\ \Omega$ and $\Theta_{TL} = 49°$. The photo of the fabricated RTPS is shown in Fig. 5.

III. MEASUREMENT RESULTS

All measurements were carried out on an Anritsu ME4647A VNA, with a two-tier TRL calibration procedure. The results across the 0 V – 16 V tuning range (shown in Fig. 6, 7 and 8) indicate that the RTPS exhibits a return loss below -10 dB across a FBW of 20 %. The presented design has a FoM equal to 115 °/dB at 10 GHz (which is a 57 % increase on the state-of-the-art RTPS at X-band [4]) and a FoM of 80 °/dB across the FBW. The design occupies 0.25 λ_g^2 of board space, as measured in Fig. 5, excluding the biasing network, and 0.42 λ_g^2 including the biasing network. This is comparable to the sizes of the designs presented in [2] and [4]. A comparison to the state-of-the-art is presented in Table II. As there are not many references to X-band RTPSs on RF PCB in literature, the simulation results of [2] are considered as well. Finally, the measured relative phase shift with respect to reverse bias voltage (V_R) is shown in Fig. 9, showing good agreement between measurement and simulation.

TABLE II
STATE-OF-THE-ART RTPS TOPOLOGIES ON SINGLE LAYER RF PCB

Reference	Frequency (GHz)	Insertion loss at 10 GHz (dB)	Max. Δφ at 10 GHz (degrees)	Area (λ_g^2)	FoM at 10 GHz (°/dB)	Min. FoM across band (°/dB)	Coupler type
[2] (simulation)	10 [a]	2.95 ± 1.15	366	0.12	89	-	Branch-line
[4]	10 [a]	4.5 ± 0.7	380	0.54 [b]	73	-	Branch-line
This work	9 - 11	2.1 ± 1.3	392	0.25	115	80	Coupled line

[a] Bandwidth not specified
[b] Estimated

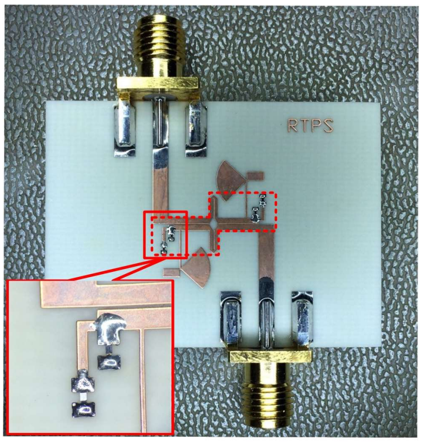

Fig. 5. Top-view of manufactured RTPS using 3-dB stub loaded coupled line coupler, with board area polygon indicated using dashed lines

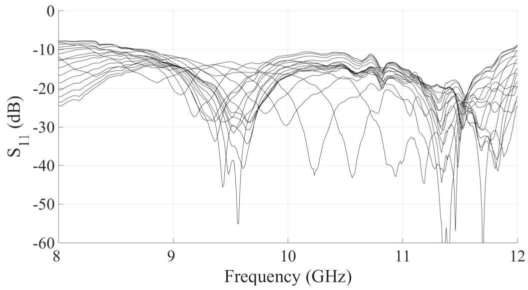

Fig. 6. Measured S_{11} magnitude of RTPS

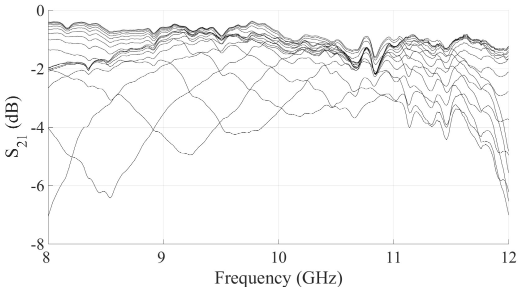

Fig. 7. Measured S_{21} magnitude of RTPS

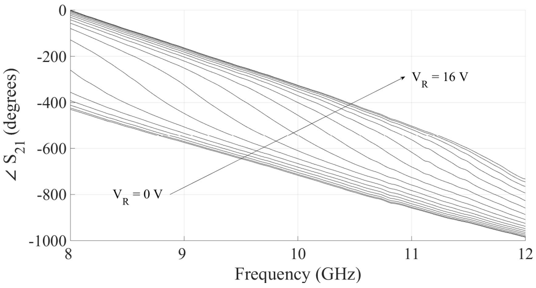

Fig. 8. Measured transmission phase (S_{21}) of the RTPS

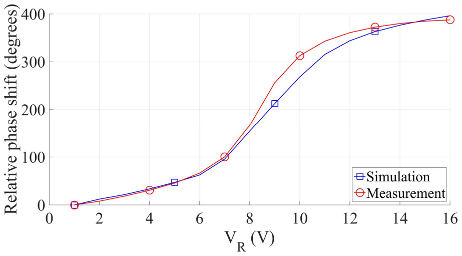

Fig. 9. Relative phase shift at 10 GHz for various reverse bias voltages (V_R)

IV. CONCLUSIONS

An X-band RTPS was presented in single layer RF PCB. Thanks to the implementation of a stub-loaded coupled-line coupler exhibiting low phase imbalance, the design operates over a 20 % FBW with a maximum relative phase shift of 392° at 10 GHz and FoM of 115 °/dB at band center and 80°/dB across the frequency band of interest, respectively. The design outperforms the current state-of-the-art in single-layer RF PCB phase shifters at X-band in terms of achievable bandwidth as well as insertion loss (57 % improvement on FoM) while having compact size.

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