Adaptive Scalar Null-Seeking Phase Alignment for Microwave Power Amplifier Combining

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Abstract— **Parallel power amplifier combining at microwave and millimeter-wave frequencies is highly sensitive to phase imbalance between amplifier paths. Small phase errors caused by manufacturing tolerances, thermal drift, or assembly variations can significantly degrade combining efficiency and increase power dissipation in the isolated port of the output combiner. This paper presents a low-complexity adaptive phase alignment technique based on scalar isolated-port power minimization using reflection-type varactor phase shifters (RTPS). The proposed method does not require vector receivers, direct phase measurement, or digital signal processing. Instead, a null-seeking control loop iteratively adjusts the phase shifter bias to minimize isolated-port power using only scalar detector measurements. The technique can be implemented using low-cost analog and digital logic components and is well suited for microwave and millimeter-wave power combining applications. Experimental proof-of-concept results demonstrate autonomous convergence toward optimal phase alignment and significant reduction in isolated-port leakage power.**

Keywords—varactor diode, phase shifter, microwave power amplifier, hybrid combiner, null seeking

I. INTRODUCTION

High-efficiency microwave and millimeter-wave transmitters frequently employ parallel amplifier combining architectures to achieve higher output power levels while distributing thermal loading across multiple devices. Hybrid-based combiners such as Wilkinson and quadrature hybrids are commonly used in these systems due to their isolation and combining characteristics. However, the overall combining efficiency is highly dependent on maintaining accurate amplitude and phase balance between amplifier paths. At Ka-band and above, even small electrical length variations caused by fabrication tolerances, thermal effects, packaging, or bias drift can introduce significant phase mismatch between channels. These mismatches result in degraded combining efficiency and increased power dissipation at the isolated port of the output combiner. Conventional correction techniques typically rely on vector measurements, digital calibration loops, or complex beamforming architectures, increasing implementation cost and system complexity. This paper presents a low-complexity adaptive phase alignment technique that minimizes isolated-port power using scalar-only measurements. The proposed approach employs reflection-type varactor phase shifters (RTPS) [1-3] together with an iterative null-seeking control loop that autonomously adjusts the relative phase between amplifier paths [4-6]. Since the method relies only on isolated-port power measurements, no direct phase detector, vector receiver, or digital signal processing is required. The proposed technique is particularly attractive for microwave and millimeter-wave systems where compactness, low power consumption, and implementation simplicity are important considerations.

II. SYSTEM ARCHITECTURE

Fig. 1 illustrates the proposed adaptive combining architecture. Two parallel power amplifier paths are combined using a hybrid combiner. Reflection-type varactor phase shifters are inserted in the amplifier paths to provide electronically adjustable phase correction. A power detector connected to the isolated port senses residual mismatch energy resulting from phase imbalance.

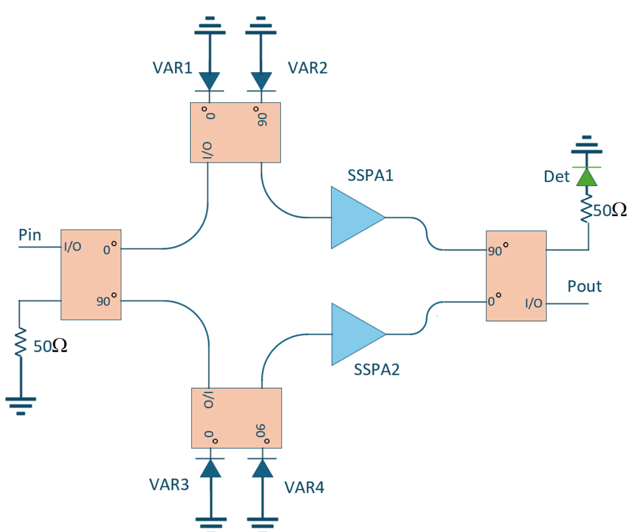


Fig. 1. System architecture. Varactors VAR1 and VAR2 are biased the same, and varactors VAR3 and VAR4 are also biased the same.

Under ideal equal-amplitude conditions, the isolated-port power is related to the phase mismatch between the amplifier paths by:

$$P_{iso} \propto \sin^2(\frac{\Delta\phi}{2}) \tag{1}$$

Where Δϕ is the differential phase error between the two amplifier channels. As the phase mismatch approaches zero, the isolated-port power is minimized and combining efficiency is maximized. The proposed technique therefore uses isolated-port power as a scalar error metric for adaptive optimization. Reflection-type phase shifters were selected due to their low insertion loss and continuous analog tuning capability at microwave frequencies. The RTPS employs varactor-loaded reflective networks coupled through hybrid structures to realize electronically controllable phase shift. The adaptive controller perturbs the RTPS control voltage and observes the resulting change in isolated-port power. By comparing measurements obtained with positive and negative perturbations, the controller determines the appropriate correction direction and incrementally updates the phase shifter bias toward the minimum-power operating point. This procedure avoids the need for vector modulation, direct phase sensing, coherent receivers or high-speed digital processing. This significantly reduces implementation complexity while maintaining adaptive phase correction capability.

III. Null-Seeking Control Method

The proposed control approach operates as a scalar null-seeking optimization loop. A small perturbation (+Δ) is temporarily added to the phase control voltage, and the isolated-port detector output is sampled to obtain an error measurement E+. The process is then repeated using a negative perturbation (−Δ) to obtain a second measurement E−. The control algorithm compares the two measurements:

- If $E_+ < E_-$, the control voltage is incremented.
- If $E_+ > E_-$, the control voltage is decremented.

This process effectively estimates the local gradient of the isolated-port power function and drives the system toward the minimum-power operating point.

IV. Experimental Controller Results

A proof-of-concept prototype was constructed to evaluate the proposed adaptive phase alignment technique. The experimental setup employed two parallel RF paths combined through a hybrid coupler together with a reflection-type varactor phase shifter controlled by the adaptive null-seeking loop. Initial phase mismatch conditions were intentionally introduced between the two paths to generate measurable isolated-port power. During operation, the controller continuously adjusted the RTPS bias voltage while monitoring the isolated-port detector output. Fig. 2 shows the controller in operation. The oscilloscope shows the three colored lines: the top blue line is the comparator voltage which is either 0 or 5V that causes the varactor bias (yellow line) to increase or decrease by Δ. At convergence the error line (violet) becomes close to zero. The timing of the circuit was intentionally made long (about 1 second) to monitor the convergence process. When convergence is reached the comparator keeps alternating between 0 and 5 V at each period, and the varactor bias accordingly varies around the optimum bias that gives minimum error by ±Δ/2. We also used an Arduino microcontroller to do the same function, and in that case once the optimum bias was reached it remained fixed at that value.

Experimental observations demonstrated stable convergence toward reduced isolated-port power over successive update cycles. As the control loop converged, the detected isolated-port power decreased significantly, indicating improved phase alignment between the amplifier paths. The adaptive loop was capable of autonomously correcting phase variations caused by manual perturbations of the phase control voltage. The system consistently converged toward the minimum isolate-port power condition within less than 10 iterations without requiring any direct phase measurement.

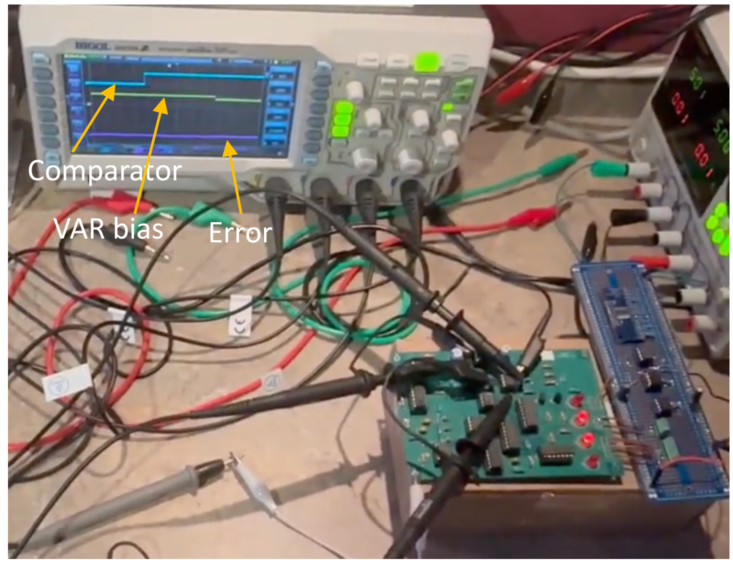


Fig. 2. Experimental monitoring of the adaptive null-seeking phase alignment loop controller.

The proposed method is expected to scale effectively to higher microwave and millimeter-wave frequencies provided suitable detector and phase shifter implementations are employed.

V. RF Design

Fig. 3 shows the RF layout of the input section of the system described in Fig. 1. The input is at port P1 is divided between the two paths using a branch line coupler and each path has a RTPS phase shifter implemented using the same branch line coupler with two varactor diodes as shown.

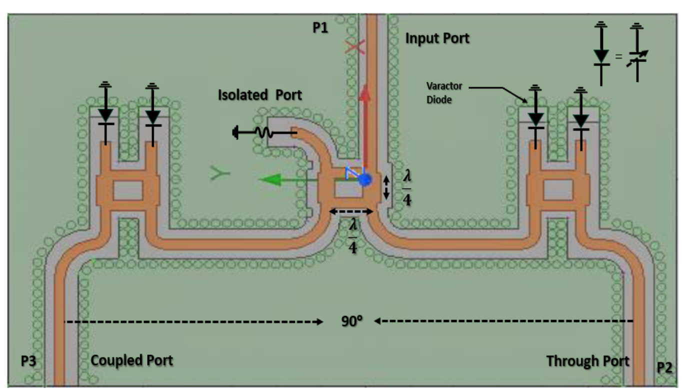


Fig. 3. RF layout of the input section of the RTPS phase shifter system.

The frequency of operation is 25 to 27.5 GHz. The varactor diodes used are MA46H120 from Macom and can operate up to 70 GHz. The nonlinear model of the varactor diode was used in Keysight ADS for the following simulations. Fig. 4 shows the simulated large signal phase adjustment range and insertion loss at the middle frequency of 26.25 GHz.

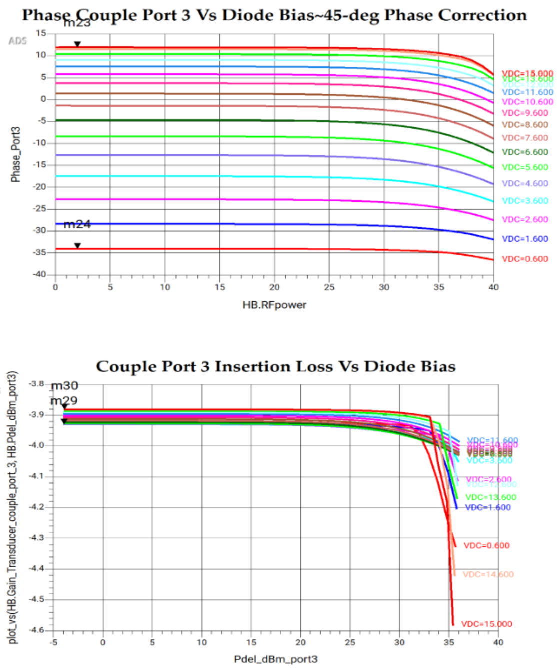


Fig. 4. Phase and insertion loss variation versus input RF power of RTPS at port 3. Port 2 has similar performance.

From the above figure it is seen that the phase variation range of each path is about 45 degrees and the insertion loss less than 1 dB above 3 dB up to 35 dBm input power. The varactor diodes DC bias varied from 0.6 V to 15 V.

VI. Simulation of Phase Aligned Power Amplifier

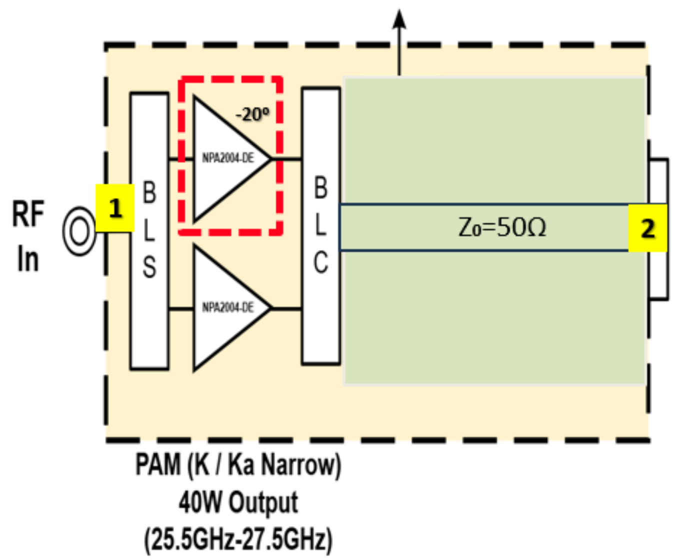
In order to study the effect on power and gain of a combined pair of power amplifiers with phase mismatch, a HB simulation was done on Keysight ADS using the Varactor's non-linear model and MMIC small signal S-parameters. For the 25 – 27.5 GHz power amplifier we used two Ka-Band GaN MMIC devices capable of 46 dBm output power as shown in Table I.

TABLE I. Ka-Band GaN MMIC Data at V_D=26 V, I_{DQ}= 2.1A

Parameter	Min	Typical	Max	Unit
Frequency	25		27.5	GHz
Gain (Small Signal)		24		dB
Output Power (at Psat, Pin=26 dBm, at 27.5 GHz)		46		dBm
PAE (at Psat, Pin=26 dBm, at 27.5 GHz)		34		%
Power Gain (at Psat, Pin=26 dBm, at 27.5 GHz)		20		dB
Input Return Loss			-8	dB
Output Return Loss			-4	dB

The simulation started with both power amplifiers having the same phase characteristics, then intentional phase variation was introduced on one amplifier using the RTPS phase shifter. Varactor diodes bias starting point was 10 V and range from 0 to 15 V. The phase shifter correction range in each side is 0° to 45°.

Fig. 5 shows the two combined amplifiers with one path's phase is offset by -20°. The blue line shows the original simulation when the two paths are aligned in phase, and the red line shows the simulation when one path is offset by -20°. We see that the output power degraded by about 1 dB. This degradation is higher than the theoretical predicted value of 0.15 dB due to the difference in impedance of the phase shifters in the two arms when they have different phase values.



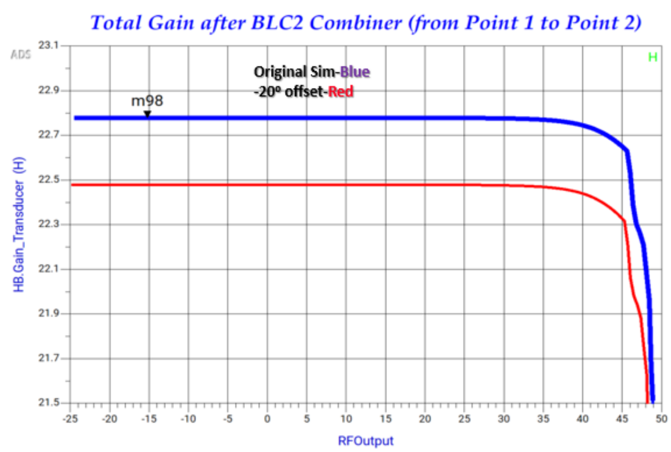


Fig. 5. Gain and power after BLC2 combiner from point 1 to point 2 with and without -20° phase mismatch.

Next, we adjusted the bias on one path varactor diodes to correct for the phase mismatch as shown in Fig 6. It is seen the output power was restored back to its original level when both paths are perfectly phase matched. The slight loss in total gain is due to change in insertion loss and Z11 changes resulting from phase adjustment.

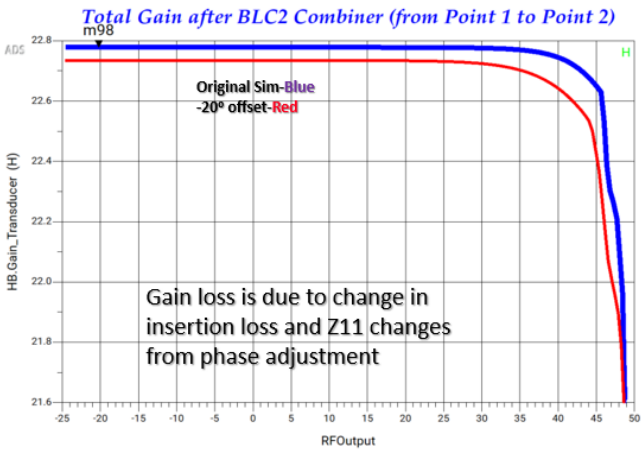


Fig. 6. Output power and gain when the phases of the two paths were aligned by adjusting the bias on one RTPS phase shifter varactors.

Fig. 7 shows the case when the phase mismatch is -30°. In this case the output power degradation is higher as expected as seen from the original red line and the offset phase blue line.

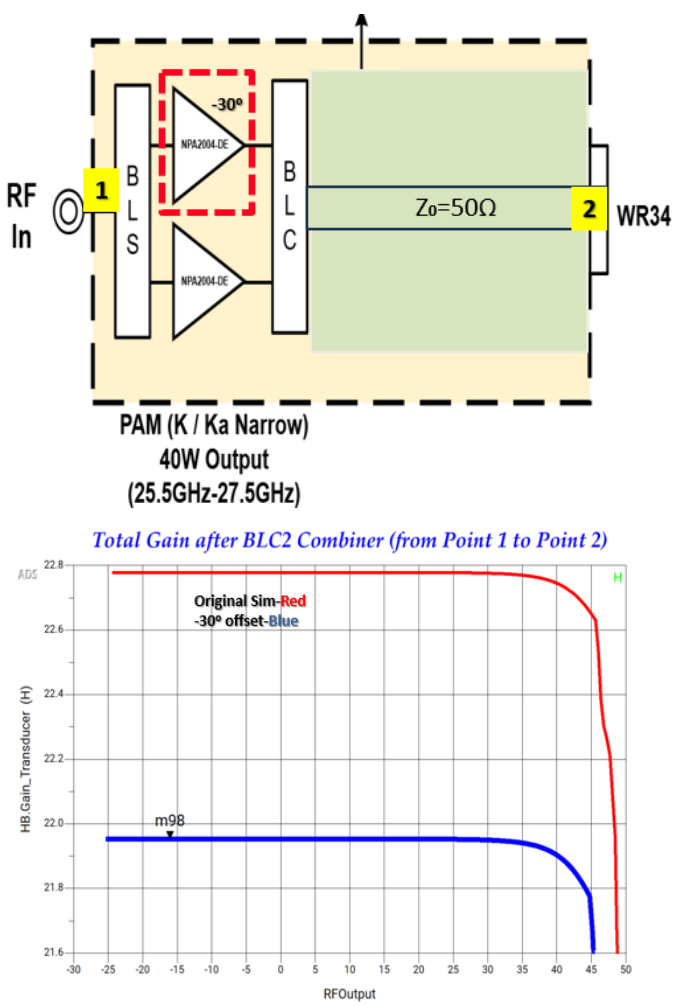


Fig. 7. Gain and power with and without -30° phase mismatch.

The simulation is shown in Fig.8 when we adjusted the bias on one path varactor diodes to correct for the phase mismatch.

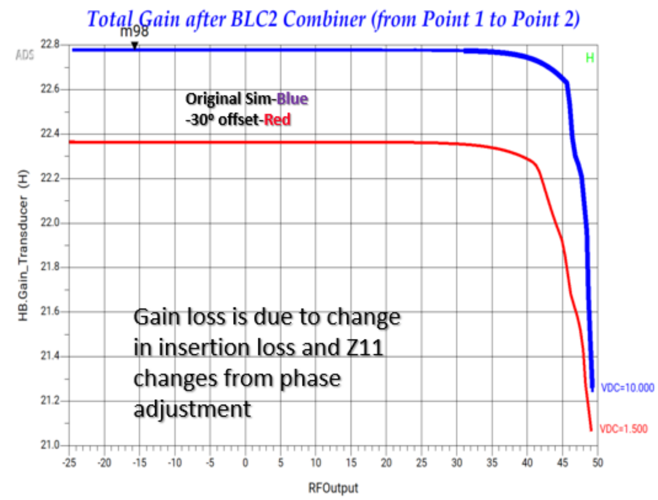


Fig. 8. Output power and gain when the phases of the two paths were aligned by adjusting the bias on one RTPS phase shifter varactors.

It is seen the output power was restored back to its original level when both paths are perfectly phase matched. The 0.4 dB loss in total gain is due to change in insertion loss and Z11 changes resulting from the new phase adjustment.

VII. Conclusion

A low-complexity adaptive phase alignment technique for microwave power amplifier combining has been presented. The proposed method uses isolated-port minimization together with reflection-type varactor phase shifters to achieve autonomous phase correction using scalar-only measurements. Experimental proof-of-concept results demonstrate successful convergence toward improved phase alignment and reduced isolated-port leakage power without the need for phase measurements or complicated calibration procedure.

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