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High Power mm-Wave Spatial Power Combiner Employing On-Chip Isolation Resistors

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***Abstract*—A spatial power combiner interfacing four power amplifiers (PAs) with isolation load resistors to a single substrate integrated waveguide (SIW) is presented. The isolation load resistors are envisioned on-chip and have been optimized to provide both the optimal active load impedance for the interconnected PAs as well as to mitigate undesired power combiner coupling effects due to non-equal excitations between PA channels. The proposed solution is compared to an ideal Wilkinson combiner in the presence of non-ideal PAs. The main performance targets are the combined output power, gain, and power efficiency at the 1-dB compression point. Simulation results demonstrate that introducing isolation load resistors allows to significantly reduce the impact of a non-uniform excitation on the combiner performance metrics.**

***Index Terms*—spatial power combining, mode converter, substrate integrated waveguide, integration, MMICs, grid amplification, parallel power combiner, quasi-optical beamforming.**

I. Introduction

Increased propagation and material losses in combination with output power limitations of semiconductor devices represent a significant challenge for modern array antenna transmitters at mm-wave frequencies [1]. This challenge could be partly overcome by combining the power of multiple active devices on each antenna array element. However, conventional circuit-level power combining networks have inherently high insertion losses, which significantly increase with the number of active devices [2], [3], especially at higher frequencies. A possible solution toward more efficient high-power generation is the multi-channel transition in substrate integrated waveguide (SIW) technology employing spatial power combining [4]. This transition allows one to directly excite the TE_{10} SIW mode with high power. It avoids the use of a lossy on-chip circuit-level power combiner while enabling the direct integration of an antenna element with multiple power amplifiers (PAs) without additional interconnecting transitions. The advantages of the proposed solution become even more apparent for an increased number of input channels.

The challenge of the proposed solution is that mutual coupling effects between multiple channels have to be taken into account from the start of the design process. In [5] this transition has been optimized under the condition of a uniform excitation assuming identical PAs. However, realistic PAs are slightly different in their amplitude-phase characteristics due to different thermal regimes, semiconductor process variations and fabrication tolerances.

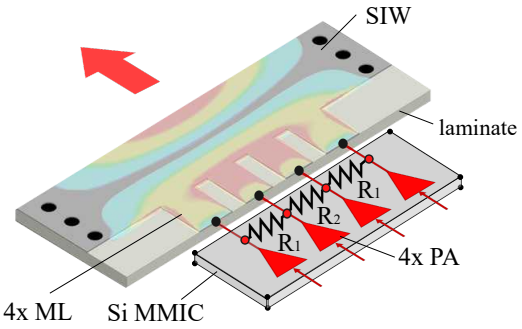

Fig. 1. The proposed spatial power combiner interfacing four on-chip amplifiers with isolation load resistors to a single substrate integrated waveguide.

This paper presents a more robust spatial power combiner (SPC) design relative to the one in [4] with enhanced performance figures in the presence of a non-uniform excitation. Fig. 1 illustrates this design solution, where three on-chip isolation load resistors are envisioned that are placed in-between the four PA outputs.

II. Concept and Operation Principle

In the original design [4] there are four input microstrip line (ML) ports with 50-Ω reference impedance and a single matched SIW port as an output. It has been optimized to realize active impedance matching for the uniformly excited case. The active reflection coefficients at the transition input ports are defined as $\Gamma_n = \sum_{m=1}^{4} A_m S_{nm}$, where S_{nm} is the 50-Ω S-parameter from ML port m to n, A_m is a random variable representing the complex excitation coefficient of port m simulating the effect of non-equal individual PAs. Generally, in order to reduce the effect of $\{A_m\}_{m=1}^{4}$ on the active reflections $\{\Gamma_n\}_{n=1}^{4}$, the magnitudes of S_{nm} have to be minimized.

This minimization issue has been addressed by introducing isolation load resistors (R_1, R_2) in-between the on-chip PA outputs (See Fig. 1). In the case of an ideal uniform excitation the voltage difference between the ML input ports will be zero implying that no current will flow into the isolation

resistors and hence there is no power dissipation. For a non-uniform excitation, the differential-mode power will be largely dissipated in the resistors. This enhanced isolation between the channels results in smaller variation of the input port active reflection coefficients Γ_n. It is pointed out that, despite the power dissipation in the isolation resistors, the expected combined output power may still be higher than the scenario without resistors. This is owing to the behaviour of the individual PAs, which deliver less power if the output load impedance is mismatched [6].

III. Numerical Validation Results

The optimal values of isolation load resistors have been found numerically by minimizing the coupling between the ML input ports while placing the resistors in-between those ports[1]. The full-wave EM-simulated 5×5 scattering parameters of the SPC are shown in Fig. 2a. Due to the symmetry of the SIW structure, the isolation load resistors between symmetric ports must be equal. An isolation resistor interconnecting the edge ports (1 and 4) cannot be implemented in practice since it requires long interconnecting lines. Thus there are only two optimization parameters, i.e., R_1 and R_2, which have been found to be 108 Ω and 150 Ω, respectively.

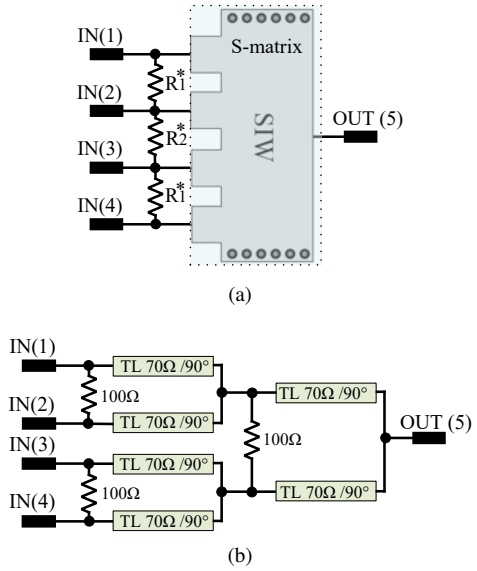

Fig. 2. Simulation models of the 4-way power combiners: (a) spatial power combiner w/ and w/o isolation load resistors, (b) ideal Wilkinson power combiner.

For comparison, a 50-Ω Wilkinson power combiner built from ideal components was used as a reference [7]. It is formed by the connection of three 2:1 combiners each employing quarter-wave transmission lines (See Fig. 2b). The central operation frequency is 30 GHz.

A. Scattering parameters

The S-parameter simulations have been performed in Keysight's ADS software. Fig. 3a shows the simulated results

[1]The on-chip isolation load resistors are assumed ideal.

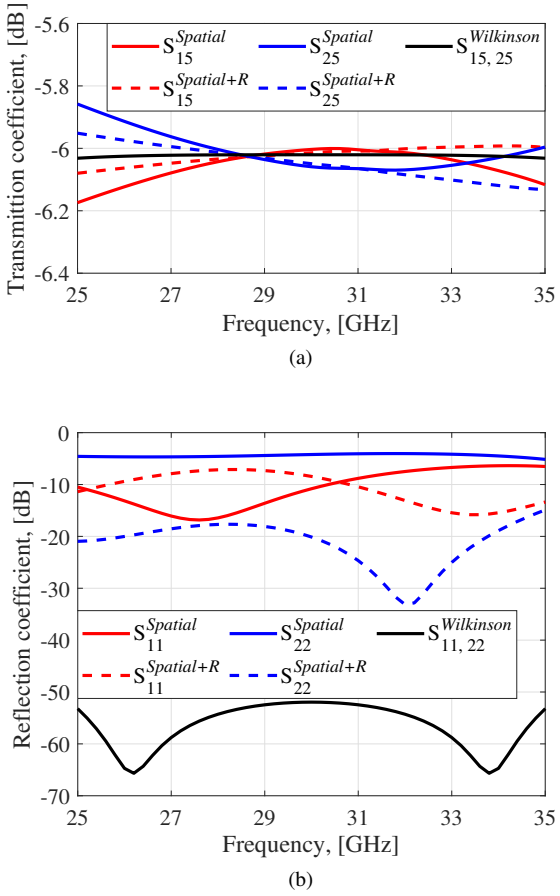

Fig. 3. (a) Simulated transmission, and (b) Simulated input port reflection coefficients coefficients of the spatial power combiner w/ and w/o isolation load resistors (dashed and solid line, resp.) and an ideal Wilkinson power combiner (black line). The results for symmetric ports are omitted.

of the SPC with and without the isolation load resistors (dashed and solid line, respectively) along with the Wilkinson power combiner case (black line). Since in the ideal 4:1 Wilkinson power combiner all input ports are identical, the transmission coefficients from each input port to the output port are equal to -6 dB over a wide frequency range. This is different for the SPC, where the input ports are not identical due to the distributed TE_{10} mode structure. Therefore, using the isolation resistors allows to minimize the differences between the input channels and hence increase the efficiency of the PAs.

Fig. 3b shows the corresponding passive reflection coefficients. As one can see, the design solution with isolation resistors allows reducing reflections from port 2. The S_{22} magnitude remains below -15 dB over the 25–35 GHz band, which is more than 13 dB lower in comparison to the case without resistors.

Fig. 4 shows the mutual coupling coefficients, where we observe much lower magnitude values in comparison to the original design with no isolation resistors. In particular, the $|S_{23}|$ and $|S_{13}|$ remain below -15 dB, and $|S_{12}|$ and $|S_{14}|$ remain below -12 dB and -7 dB, respectively, over the 25–

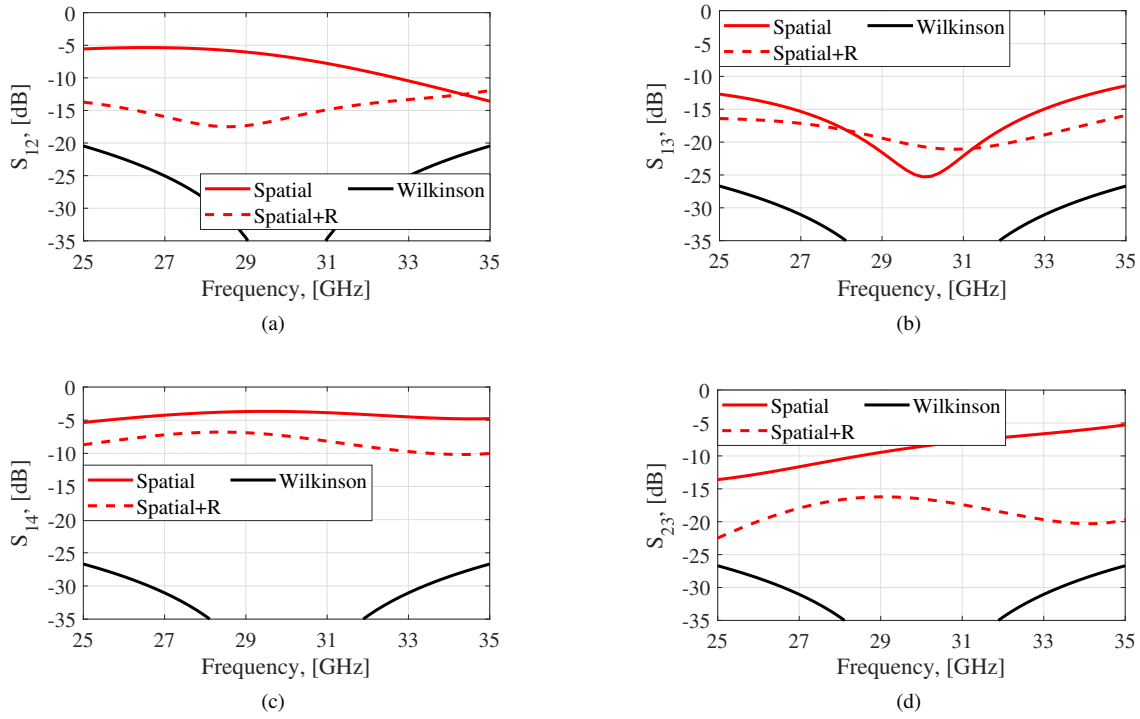

Fig. 4. Simulated mutual coupling between the input ports of the spatial power combiner w/ and w/o isolation load resistors (dashed and solid lines, respectively) and an ideal Wilkinson power combiner (black line). The results for symmetric ports are omitted.

35 GHz band. The relatively high level of $|S_{14}|$ could be reduced by introducing another resistor between the edge ports. The ideal Wilkinson combiner intrinsically has a good input matching and exhibits excellent isolation properties.

B. Total performance in presence of PAs

In order to evaluate the performance of the power combiners in conjunction with non-identical PAs, a simulation test-bench has been proposed (See Fig. 5). It has a single 50-Ω input port interfaced to an ideal 1:4 power splitter. The power splitter feeds an array of identical common-base PA-modules in SiGe HBT technology [8]. The power amplifiers are power-matched to the 50-Ω load impedance.

In practice, phase variations of the PA gain dominate over amplitude drifts. This effect is emulated by four independent phase shifters with normally distributed phase values $\{\phi_n\}_{n=1}^{4}$. The normal distribution is defined by the mean value $\mu = 0°$ and standard deviation $\sigma = 10°$. The outputs of the PAs are interfaced to the matched 4:1 power combiners as discussed above.

The performance of such a joined active structure has been investigated in terms of PA metrics. Fig. 6 shows the gain, output power, and efficiency of a single PA at the 1-dB compression point (P1dB) over the 25–35 GHz band. Ideally, the P1dB output power level after combining four PA channels should be 6 dB higher than that of a single PA, whereas the gain and efficiency values should remain the same. However, these performance targets are not feasible for realistic devices where phase variations are not negligible.

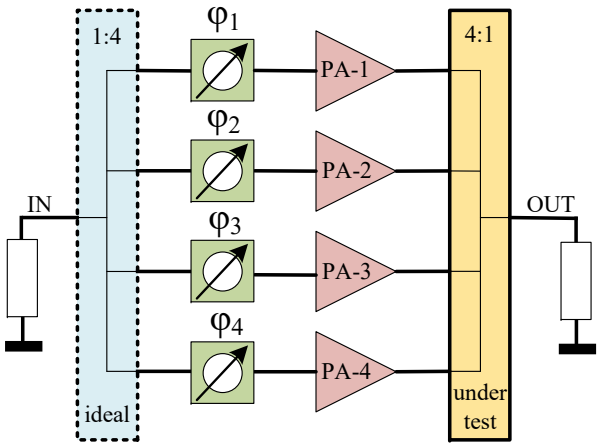

Fig. 5. Simulation test-bench for combined PA performance evaluation in the presence of normally distributed phase errors, used for the ideal Wilkinson power combiner and the spatial power combiners w/ and w/o isolation load resistors.

Fig. 7 shows the active reflection coefficients at the SPC input ports for the uniform excitation case. The level of reflections are below -25 dB over the 25–35 GHz band for all combiners, as expected.

Fig. 8 shows the simulated yield of the combined PAs as obtained with the test-bench in Fig. 5. The yield analysis is based on statistical variations of the introduced phase errors $\{\phi_n\}_{n=1}^{4}$. This is needed to determine how many possible

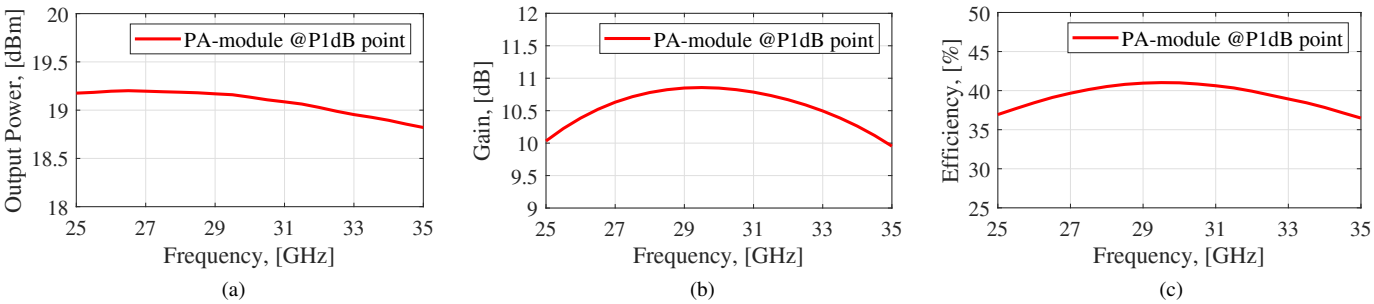

Fig. 6. Simulated performance of a single PA-module @P1dB compression point: (a) output power; (b) gain, and; (c) efficiency.

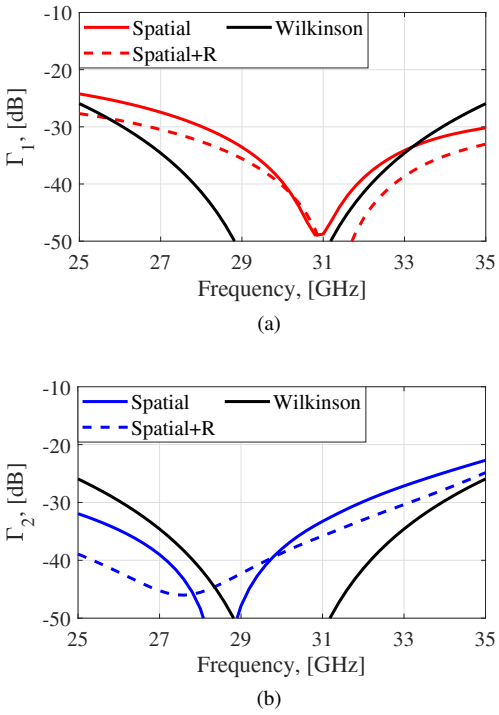

Fig. 7. Simulated input port active reflection coefficients (uniform excitation) of the spatial power combiner w/ and w/o isolation load resistors (dashed and solid lines, respectively) and the ideal Wilkinson power combiner (black). The results for symmetric ports are omitted.

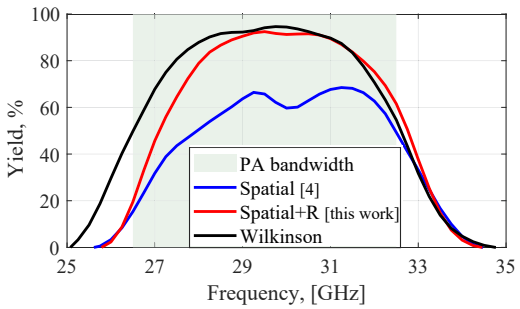

Fig. 8. Performance yield of the PAs in conjunction with the spatial power combiner w/ and w/o isolation load resistors (red and blue lines, respectively) and an ideal Wilkinson power combiner (black line) in the presence of normally distributed phase errors with $\sigma = 10°$. Positive performance yield if @P1dB, Gain $\geq$ 10.5 dB, Power $\geq$ 24.5 dB, Efficiency $\geq$ 35%.

phase combinations satisfy the following performance specifications which be met simultaneously:

- Output power[2] $\geq$ 24.5 dBm;
- Gain[2] $\geq$ 10.5 dB;
- Power efficiency[2] $\geq$ 35 %.

The colored region in Fig. 8 shows the operating bandwidth of a single PA-module, where the desired specifications could be potentially satisfied. It is seen that more than 90 % and 80 % of the realizations satisfy the desired specifications over the 29–31 GHz and the 28–32 GHz bands, respectively. It confirms that the proposed spatial power combiner with isolation load resistors is a good alternative to the conventional Wilkinson power combiner in terms of a low sensitivity to a non-uniform excitation.

[2] Performance is at 1-dB compression point.

IV. Conclusion

A low-loss spatial power combiner with enhanced port-isolation properties has been optimized and examined. It avoids the use of a lossy on-chip circuit-level power combiner while enabling the direct integration of an antenna element. The isolation load resistors allow reducing the coupling effects between PA channels, without increasing the losses in the case of a uniform excitation. The power combining performance in the presence of a non-uniform excitation caused by non-incidental PAs has been statistically analyzed. Simulations show that the proposed solution allows to significantly reduce the negative impact of a non-uniform excitation on the overall output power, gain, and power efficiency at the 1-dB compression point.

The concept is expected to play an important role in high-power MMICs, where both low insertion losses and optimal active device load matching are important requirements.

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