

A 120-W X-Band Spatially Combined Solid-State Amplifier

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Abstract—In this paper, we present new results in the development of a broad-band spatial power-combining system implemented in a standard X-band waveguide environment. Using 24 off-the-shelf GaAs monolithic-microwave integrated-circuit (MMIC) power amplifiers integrated with tapered-slot antenna arrays, the new combining circuit produced up to 126-W maximum power output with a gain variation of ± 1.9 dB within the band of interest (8–11 GHz). This hybrid circuit combiner is transparent to the device technology, and also provides an excellent heat-sinking capacity, sustaining as much as 415 W of dc power consumed by the MMIC amplifiers. The modular architecture allows easy maintenance, variable output power level, and modular assembly. Results on graceful degradation are also presented, showing superb tolerance to device failure.

Index Terms—Finline structure, solid-state power amplifier, spatial power combining.

I. INTRODUCTION

POWER-COMBINING techniques present a viable solution to realize solid-state sources and amplifiers at microwave and millimeter-wave frequencies, with RF power levels that currently cannot be achieved by a single solid-state device. In large-scale power-combining applications, quasi-optical, and/or spatial power-combining schemes are favored over the traditional corporate methods in that the combining loss remains fixed as the number of active device increases.

In order to realize a solid-state power amplifier with a significant RF power level, large-scale integration of several high-power amplifiers is required. The combining circuit should be as compact as possible, but the size is limited by the physical area of the devices and associated biasing circuitry, antennas, and thermal management issues. The heat-sinking capacity is especially important in order to avoid performance degradation and even device failure, and the size of the package for appropriate heat sinking is strongly linked to the choice of cooling measures.

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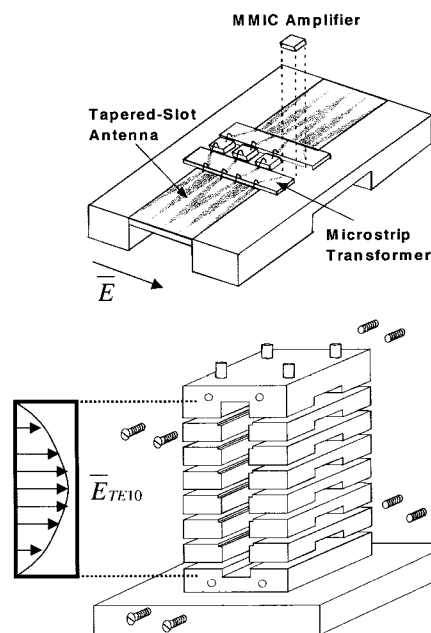


Fig. 1. Schematic illustration of the combiner design.

In an earlier paper, we reported a broad-band 41-W result for a waveguide-based spatial power-combining circuit that was implemented by using eight 6-W monolithic-microwave integrated-circuit (MMIC) amplifiers [1]. In this paper, we present an extension of that work using 24 6-W MMIC amplifiers, which was aimed at producing >100 -W performance and addressed the above-mentioned issues. The underlying objective of the effort was to demonstrate a combiner technology with a high-combining efficiency that can be extended to large numbers of devices and a variety of device technologies.

II. CIRCUIT DESIGN

Alexanian and York [2], [3] proposed the original idea, from which the 120-W spatial combiner was derived. The combiner circuit consists of six identical “trays,” as shown in Fig. 1, each of which contains four input/output broad-band tapered-slot antennas integrated with four MMIC amplifiers via a slotline-to-microstrip transition. When all the trays are stacked together, along with the top/bottom covers, an active antenna array is constructed and two standard WR-90 waveguide openings are formed at the input/output ports. All the components are held in tight positions with screws.

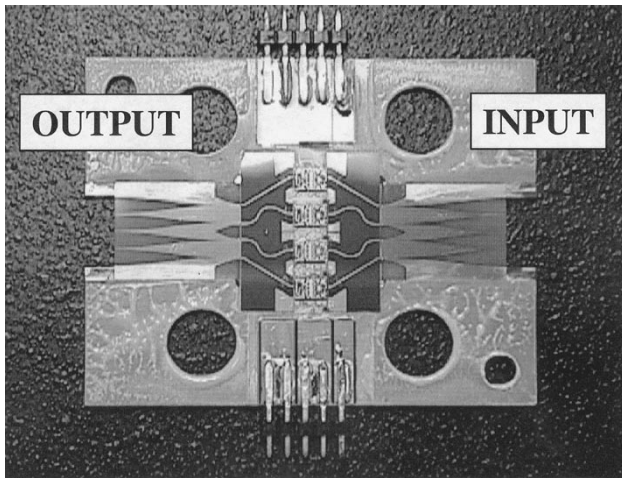


Fig. 2. Top view of the circuit layout on a single tray.

The body of the test fixture was made of copper, which has excellent thermal conductivity. The MMIC amplifiers were attached directly onto the test fixture and efficient heat-conducting paths were created right underneath the MMIC's. The orientation and distribution of the E -field at the opening is also shown in Fig. 1, which corresponds to a TE_{10} -mode operation in a standard waveguide.

The circuit layout on a single tray is shown in Fig. 2. Each MMIC amplifier, which was premounted on to a heat-spreader, was attached directly onto the test fixture using conducting silver epoxy and cured subsequently at $175\text{ }^{\circ}\text{C}$. A microstrip taper was used as a broad-band impedance transformer between the tapered-slot antenna and MMIC amplifier because the characteristic impedance at the taper end of the antenna was experimentally verified to be $70\ \Omega$ and the MMIC amplifier required a $50\text{-}\Omega$ match at the input. The microstrip tapers have meandering shapes so that the taper lengths and the resulting phase differences remain the same among them.

All planar structures, such as the tapered-slot antennas and microstrip transformers, were defined on 10-mil-thick aluminum-nitride substrates with $3.8\text{-}\mu\text{m}$ thickness of gold, by using standard photolithography processes. For both dc and RF purposes, 1-mil bondwires were used to realize interconnections. The square-pin headers carried the gate and drain biases, along with the ground line, to the MMIC amplifiers. Note that more MMIC amplifiers can be laterally added to the space adjacent to the existing ones and, hence, more active elements can be integrated into the combiner circuit.

In order to reduce the combining loss, the shape of the antenna taper has to be chosen properly so that return loss can be minimized within the frequency band of interest [5], as demonstrated in our previous 40-W combiner circuit. For convenience, the previous antenna design was used and scaled to accommodate four, instead of two, antennas on each tray. Through measurements were performed in order to examine the insertion loss characteristics of the passive structure. The layout of the test circuit is shown in Fig. 3, which consists of a back-to-back configuration of splitting/combining structure (tapered slot antennas and microstrip transformers) with $50\text{-}\Omega$ microstrip lines used as through elements.

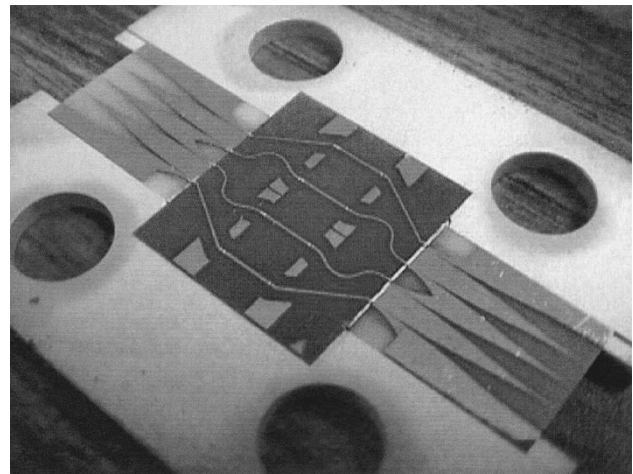


Fig. 3. Layout of the test circuit for the through measurements.

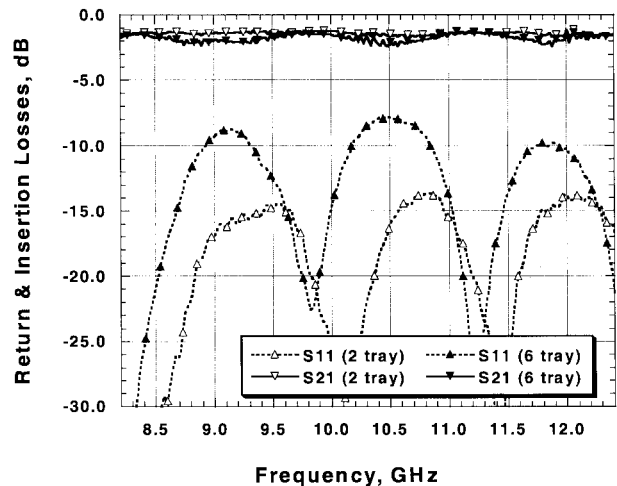
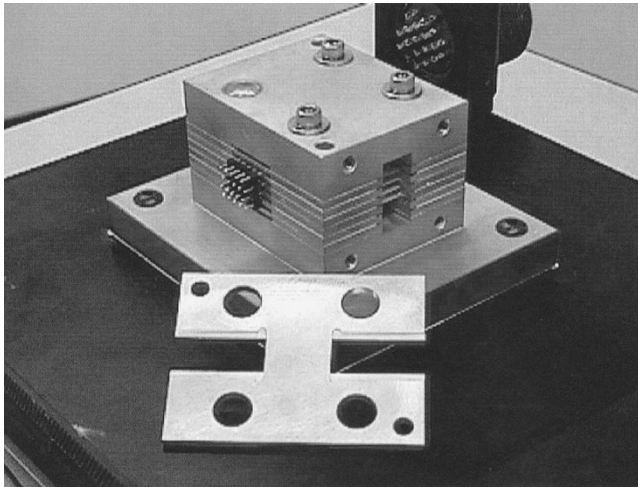


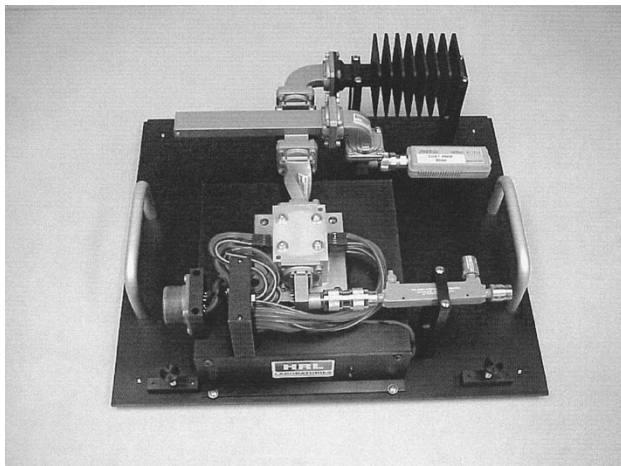
Fig. 4. Insertion loss and return loss for the 2×4 and 6×4 arrays based on the 100-W system, with $50\text{-}\Omega$ microstrip lines used as through elements.

Two- (4×2 array) and six-tray (6×4 array) measurements were made, as shown in Fig. 4. The insertion loss was between -1.1 and -1.7 dB for the two-tray case and between -1.3 and -2.4 dB for six-tray, and the return loss was better than -14 dB for the entire X -band in the two-tray case, while -7.5 dB in the six-tray case. The results suggested the properties of wide-band and low insertion loss for the combining system. However, as the number of trays increased, the insertion loss and return loss deteriorated, which was a direct effect due to the fact that the antenna structure was originally optimized for a 2×2 configuration in a 40-W system [1].

An overview of the complete combiner system, along with an empty tray in front of the combiner, is shown in Fig. 5. A heat sink equipped with fins and a rotating fan was used and located right beneath the power combiner to enhance the heat-dissipating capacity. The combiner design adopted a modular architecture, adding a great flexibility to circuit operation. Empty trays can be used to replace active "trays" if a smaller active antenna array is desired. Extra (active) trays can be pre-made and reserved in case any malfunctioning tray



(a)



(b)

Fig. 5. (a) Assembled combiner circuit mounted on air-cooled heat sink, showing an empty tray. (b) Completed assembly includes test instrumentation and biasing.

needs to be replaced. Moreover, medium-scale fabrication for the combiner circuit is possible since all the trays are identical in terms of circuit layout and functionality.

Thermal simulations were performed for the system to ensure that the MMIC's would be operating below their rated maximum operating temperature. A simulated temperature distribution is shown in Fig. 6. The simulation assumed 5-W RF output power for each MMIC at 30% of power-added efficiency (PAE), and a copper fixture with a base temperature held at 25 °C. The maximum temperature rise occurs beneath the MMIC's on the top tray, and is approximately 77 °C or 52 °C above ambient. This is within acceptable limits for this MMIC technology.

III. COMBINER PERFORMANCE

Measurements were performed for a six-tray configuration, corresponding to an active 6 × 4 antenna array. Twenty-four commercial GaAs MMIC power amplifiers (TGA9083-EEU) were used in the combiner circuit. The nominal output power for each MMIC amplifier is 5 W at 7-V drain bias, 6 W at

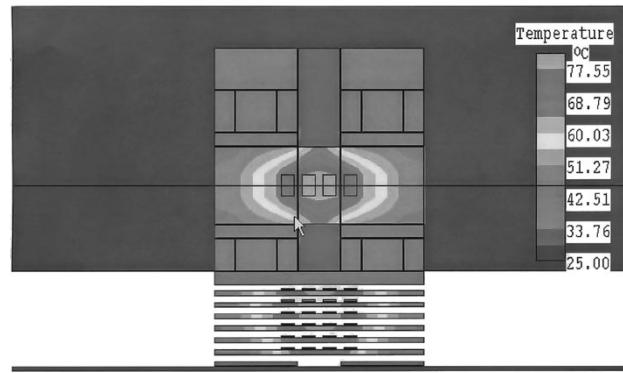


Fig. 6. Thermal simulation of six-tray combiner system with four MMIC's per tray (24 MMIC's). The simulation assumed a 5-W RF output for each MMIC at 30% of PAE and copper trays.

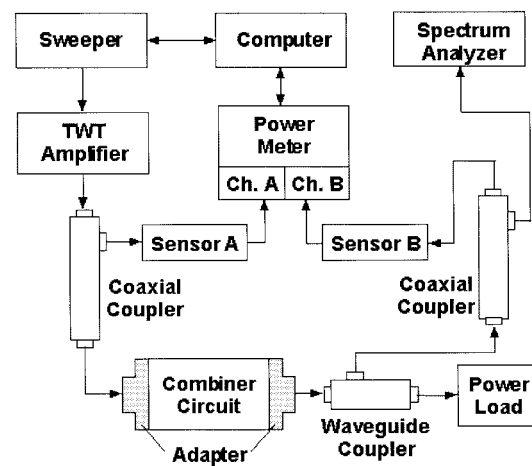


Fig. 7. Power measurement setup.

8 V, and 8 W at 9 V over the range of 6.5–11 GHz, with a small-signal gain of 19 dB and 33%–40% of PAE. On-chip active gate biasing was used to simplify the biasing setup, which required a negative supply of −5 V. Chip capacitors were used at gate/drain bias to avoid dc oscillation.

Fig. 7 shows the setup for the power measurement, in which a window-based user-interactive computer program was developed and used for automatic instrumentation control and data acquisition. A waveguide coupler, which remains robust at elevated temperature, along with a high-power 50-Ω load was utilized at the output port of the combiner circuit to ensure proper termination since more than 100 W of output power was expected. Prior to the measurements, a calibration procedure was performed with extra care so that the RF power level at the input/output port of the combiner circuit could be determined based on the readings from power sensors *A* and *B*. A spectrum analyzer was used to monitor the output spectrum, especially oscillations.

The power measurement results for the 6 × 4 array with $P_{in} = 38$ dBm are shown in Fig. 8. A maximum output power of 126 W was observed at 8.1 GHz, with a corresponding gain more than 13 dB and PAE in excess of 33%. The gain varied between 9.3–13.1 dB from 8 to 11 GHz, with only less than ±1.9-dB gain variation. The gain variation was greater than expected and might result from the fact that the

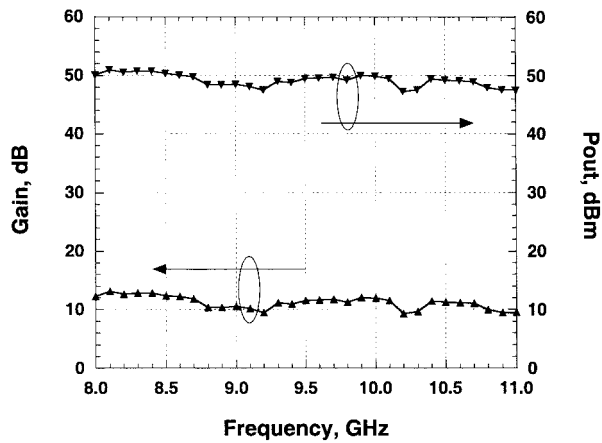


Fig. 8. Power measurement result for the 6×4 arrays at $P_{in} = 38$ dBm and $V_d = 8$ V.

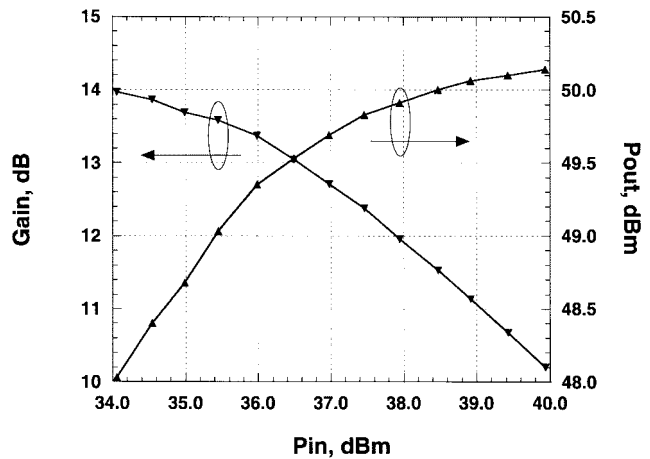


Fig. 10. P_{out} versus P_{in} near saturation for the 24-MMIC system.

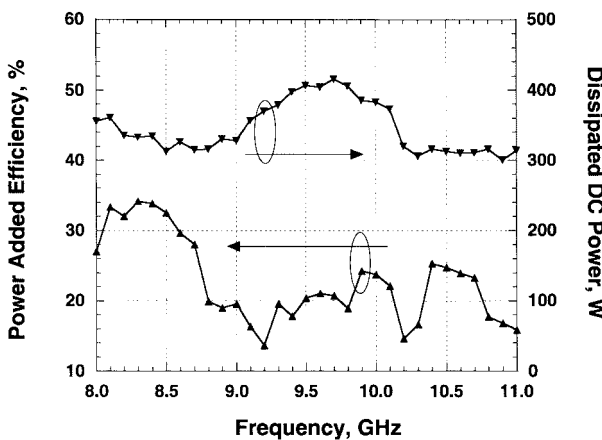


Fig. 9. PAE and dissipated dc power for the 6×4 arrays at $P_{in} = 38$ dBm and $V_d = 8$ V.

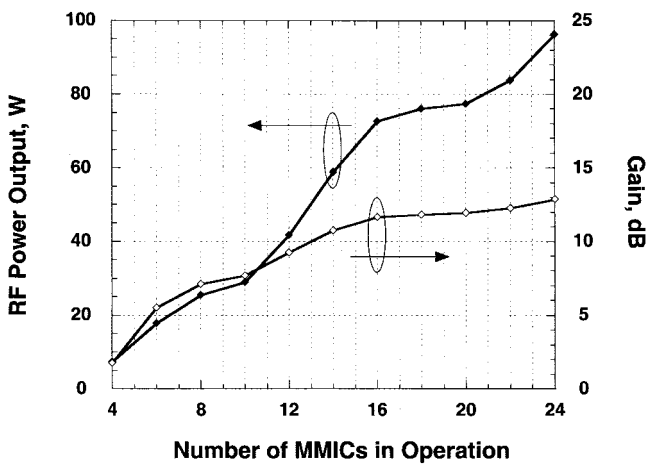


Fig. 11. Graceful degradation characteristics for the 6×4 arrays, at $f = 8.1$ GHz, $P_{in} = 37$ dBm, and $V_d = 7$ V.

shape of the tapered slot antennas was not optimized for best performance. Also highly possible, nonideal circuit assembly, such as bad attachments for microstrip taper sections and MMIC amplifiers, might be another cause. Another possibility was the longer than expected bondwire connections in the RF paths in this particular combiner circuit.

The MMIC amplifiers were operated under continuous wave (CW) condition with frequency sweep up to 11 GHz, at which the performance of the MMIC amplifiers started to degrade. The total of 24 MMIC amplifiers, which were biased at 8 V of drain voltage, consumed about 43 A of drain current and 246 W of dc power on average. As shown in Fig. 9, the dissipated dc power presented a significant swing in value between 300–400 W during the frequency sweep. The PAE of the combiner circuit fluctuated between 13% and 34% as frequency varied and, in general, correlated well with the variation of dissipated dc power—the PAE decreased as the dissipated dc power increased and vice versa.

Fig. 10 shows output power versus input power for the array at 8.1 GHz, biased at 8 V. The sweep was focused around the range near saturation. It was found that some in-band oscillations occurred for weak drive power, which prevented the measurement of a full power sweep well into the linear gain

region. The output capacitance of MMIC amplifier changes as the drive power level changes. Therefore, the oscillations can be suppressed with high drive power since the oscillation condition no longer exists. However, similar problems in the past with earlier versions of the array [1] were solved by the addition of larger RF bypass capacitors near the MMIC's, and more careful attention to equalization of bias to the MMIC's. These steps have yet to be performed for the present system.

The characteristics of graceful degradation, which is an important attribute of the combiner circuit, were investigated (at 8.1 GHz) and the results are shown in Fig. 11. MMIC amplifiers were turned off intentionally, beginning from the ones on outer trays toward the inner trays, by turning off the gate and drain bias supplies. It is obvious to see that the output power and gain gradually reduced as the number of operating amplifiers decreased. The combiner circuit lost about 57% of original output power when half of the devices were turned off. Ideally, it should be 50% if the devices were ideally isolated. No catastrophic failure was observed as a result of the loss of these amplifiers.

To reduce the thermal resistance between the MMIC amplifiers and heat sink, nonconductive thermal grease was applied between adjacent trays and top/bottom covers. However, the

thermal grease resulted in extra electrical resistance between the groundings of adjacent trays. Individual grounding was provided to each tray to avoid possible oscillation problem. Thermocouples were used and attached to the surfaces of the top cover and base plate of the test fixture during measurements. In general, the temperatures were approximately 60 °C and 30 °C at the top cover and base plate, respectively, during the frequency sweep, indicating an excellent heat-sinking property provided by the combiner circuit, and also a good agreement with the thermal simulation of Fig. 6.

IV. CONCLUSION

In this paper, we presented the preliminary results for a newly designed spatial power-combiner circuit based on 24 off-the-shelf GaAs MMIC power amplifiers, integrated with 6×4 tapered finline arrays. A maximum output power of 126 W (CW) was observed at 8.1 GHz, with a corresponding gain greater than 13 dB and PAE in excess of 33%. Gain variation was less than ± 1.9 dB covering the frequency ranging from 8 to 11 GHz. The combiner circuit also presented a graceful degradation property, where the RF power output degraded gradually while the MMIC amplifiers were turned off intentionally to emulate device failure. The heat-sinking property of the combiner circuit has been verified during power measurements, with as much as 415 W of dc power dissipated by the MMIC amplifiers.

The hybrid-circuit approach also allows circuit designers the flexibility of choosing active devices based on different technologies, thanks to the modular design of the combiner circuit, enabling easy maintenance, variable output power level, and potential medium-scale fabrication. It is worth mentioning that higher RF power output is possible by using an over-moded waveguide structure, which can be easily achieved by stacking more active trays together. The results thus far have been encouraging, suggesting a promising outlook for our combining system to compete with the currently dominating traveling-wave tube amplifiers (TWTA's) in high-power applications.

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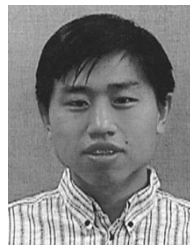
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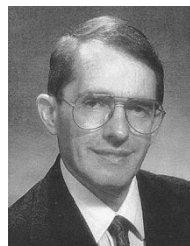
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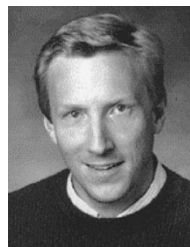
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