Broadband Spatially Combined Amplifier Array Using Tapered Slot Transitions in Waveguide

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***Abstract*— Most reported spatially combined or quasioptical amplifier arrays exhibit resonant narrowband performance (<10%) and have not addressed thermal management issues. We report a waveguide-based spatial combining scheme using broadband tapered-slot transitions, capable of realizing full waveguide band coverage (40% fractional bandwidth) with good thermal properties. An X-band prototype using eight medium-power GaAs monolithic microwave integrated circuits (MMIC's) produced an output power of 2.4 W and 9-dB power gain at 1-dB compression, with a combining efficiency of 68% and <±1-dB gain variation over the full waveguide band (8–12 GHz).**

***Index Terms*—Power amplifiers, spatial power combining, tapered slot antennas, waveguide transitions.**

I. Introduction

QUASIOPTICAL or spatially combined amplifier arrays attempt to integrate a large number of devices in a planar radiating structure. Arrays have been reported in a grid configuration [1]–[3] or using more conventional planar antennas such as patches and slots [4], [5]. In both cases, the devices are distributed in a single layer transverse to the beam propagation, and consequently small resonant antennas must be used, limiting the bandwidth. Input/output isolation also complicates the design and typically requires either a multilayer geometry or the use of two orthogonal polarizations for input and output signals, along with external polarization control components. The use of separate transmit and receive antennas further limits the bandwidth. A more severe complication is thermal management. In most reported schemes heat removal can only take place through the array periphery, which would limit the size of the array to keep the central array elements at a specified operating temperature.

We report a waveguide-based combining scheme with broadband performance and exceptional input/output isolation and heat-sinking properties. In this approach, one or more circuit-combined power amplifier circuits are integrated between nonresonant tapered-slot antennas and stacked vertically to form a two-dimensional (2-D) power "card" (Fig. 1). These cards can then be stacked together and placed in a metallic waveguide enclosure, which confines the energy and also serves as a heatsink. A good thermal path between the active circuit and waveguide walls is established using a high thermal conductivity substrate, such as Aluminum Nitride, and a metallic mounting structure beneath the active circuit that also rigidly holds the power card in place (Fig. 2). Each circuit is planar and therefore can be fabricated monolithically, but the entire array is a three-dimensional (3-D) construct.

Like most spatial combining schemes, the combining efficiency is potentially high in a well-designed array, making the approach well suited to combining large numbers of devices. The dominant loss mechanism is conductor loss in the antenna metallization, but since each array element is operating in parallel, there is little or no penalty incurred when adding more devices, which is an advantage over conventional combining schemes. In principle, the waveguide walls can be flared out to accommodate more devices, but this also requires careful attention to potential moding problems; in this work, a standard WR-90 waveguide cross section is used.

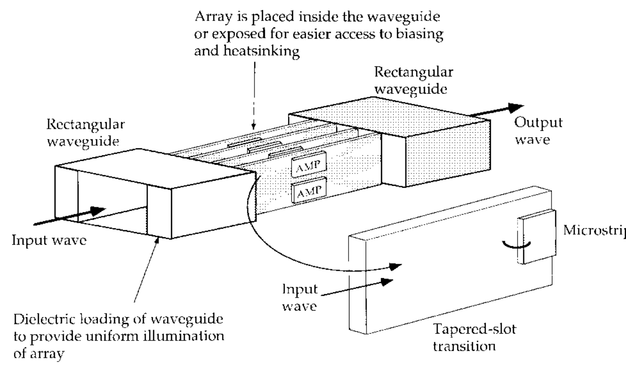

Fig. 1. Perspective view of 2 × 4 amplifier array placed between X-band waveguides.

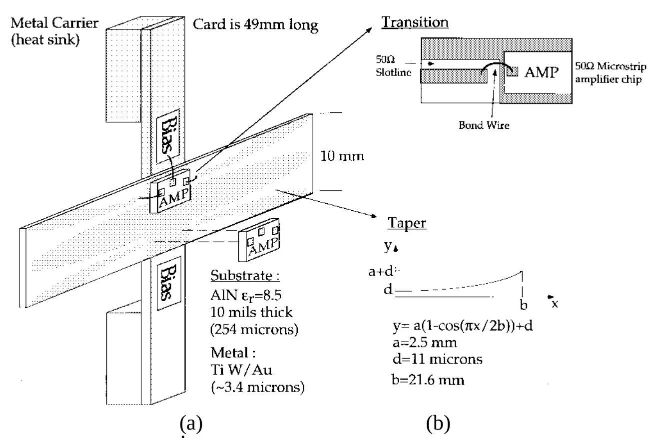

Fig. 2. (a) Perspective view of single card mounted on heat-sink metal carrier. (b) Transition from slotline to microstrip and taper function.

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The approach is compatible with conventional monolithic microwave integrated circuits (MMIC's), using an appropriate transition from slotline to microstrip or coplanar waveguide, as will be demonstrated. The nonresonant nature of the tapered-slot antennas results in broadband performance, limited primarily by the waveguide environment; full-waveguide band coverage (40%) has been obtained in the experiments. The use of traveling wave antennas also provides good input/output isolation and consequently does not require the use of orthogonal polarizations to decouple input from output. It also provides additional space in the direction of propagation for additional device integration. The multilayer approach and metallic enclosure provide larger surface area for thermal management. Finally, this approach is highly modular and compact.

II. Concept and Fabrication

Tapered slot antennas have been investigated by a number of researchers [6]–[8]. These antennas are broadband, have rotationally symmetric patterns, and have an input impedance that is essentially given by the characteristic impedance of the feed slotline. The same attractive features are observed and exploited in broadband finline transitions in waveguide [10], [11]. Recently, this work has been extended to a 3-D array of tapered slotlines for a Gaussian beam waveguide [9]. Although a single tapered slot antenna has a lower frequency limit set by the aperture size, this limitation does not strictly apply in an array environment, as shown in [9]. This can be easily understood on the basis of an equivalent waveguide analysis of an infinite array of tapered slots. The same observation applies in a waveguide environment and means that a number of tapered slot or finline structures can be integrated vertically on a single substrate. If several such substrates are stacked together in the waveguide, as suggested in Fig. 1, the potential for power combining is clear.

To verify the array concept shown in Fig. 1, we have constructed an array from four substrates, each of which integrates two paired input/output slot transitions vertically, which are in turn coupled to a microstrip-based medium-power GaAs MMIC. A 10-mil-thick (254 μm) AlN substrate was chosen for its high thermal conductivity ($\kappa = 1.5$–1.7 W/cm·C). The metallization pattern was etched using standard photolithographic techniques in 3.4 μm of evaporated gold. A simple cosine taper was used for the antennas (Fig. 2). The slot-to-microstrip transition was a simple bond wire connecting one side of the slot to the top microstrip metallization, with the other side forming the microstrip ground plane. Measurements of the passive array structure (amplifier chips replaced by through lines) indicated approximately 1.5-dB insertion loss.

The active devices used in this work (donated generously by Texas Instruments) were two-stage medium-power GaAs MMIC amplifiers, available commercially from Texas Instruments. The center four elements of the array used TGA8014-SCC amps [6–18 GHz, 0.5-W output power at 1-dB gain compression, 11-dB small signal gain, and 16% power-added efficiency (PAE)]. For the edge elements of the array, similar TGA8014-XCC amps were used (6.5–18 GHz, 0.4-W output at 1-dB compression, 10.5-dB small-signal gain, and 13% PAE). The two chips are identical in every way except the biasing configuration. Note that a key requirement for this method is an unconditionally stable amplifier circuit, which is a feature possessed by these circuits.

The chip MMIC's were mounted on the card using conducting epoxy; this is clearly not optimal for heatsinking, but facilitated easy assembly for this preliminary test. Bias capacitors where mounted in close proximity to the circuits. Each card was mounted on a metal carrier whose purpose was to provide heat sinking, mechanical support, and convenient access to biasing circuitry (Fig. 2). The card was similarly attached to the carrier with silver epoxy for convenience. The thickness of the carrier established the substrate spacing in the waveguide. Four of these assemblies were stacked to form a 2×4 array, which was inserted between two X-band waveguides. The penetration depth of the array in the waveguides was initially left as an independent variable for performance adjustment, but in a practical system a fully enclosed package would be preferred.

Power incident on the array from the input waveguide is distributed among the cards following the nonuniform dominant-mode field profile, which could lead to inefficient operation of some array elements. This can be addressed in several ways: using dielectric sidewall loading; increasing the device size or packing density in the central cards; varying the biasing configuration for peripheral array elements; or simply using a nonuniform card-to-card spacing. In our experiments, nonoptimal uniform card spacing with no sidewall loading was used for simplicity. The effects of the nonuniform incident field are not pronounced because the cards were closely spaced and placed in the center of the waveguide. Finally, slightly lower power amps were used for the two edge cards compared to the two at the center.

III. Measurements

The bias applied to the drain of each TGA8014-SCC was 7.4 V at 350 mA Similarly, the TGA8014-XCC used 7 V at 300 mA; these are not the maximum allowed settings specified by the manufacturer. Both CW and pulsed-bias measurements were performed. A low duty cycle pulsed-bias resulted in approximately 0.5 to 1 dB improvement in power gain, a small but significant improvement that is attributed to the use of epoxy rather than solder in the circuit assembly, which interrupted the otherwise good thermal path from the amplifiers to the metal carrier/heatsink. A small-signal measurement showed a gain of approximately 10 dB over the full waveguide band. A 1-dB gain compression was observed when fed by approximately 0.25 W as expected. The measured results (Fig. 3) show 40% bandwidth covering the entire 8–12 GHz WR-90 band. A peak gain of 9.2 dB (Fig. 3) and an output power of 2.4 W was observed, with less than ± 1 dB gain and power variation over the full waveguide band. This corresponds to a PAE of 11% and a combining efficiency of 68%, based on the manufacturer's specifications. This combining efficiency suggests a system insertion loss of 1.76 dB, consistent with our passive array measurements.

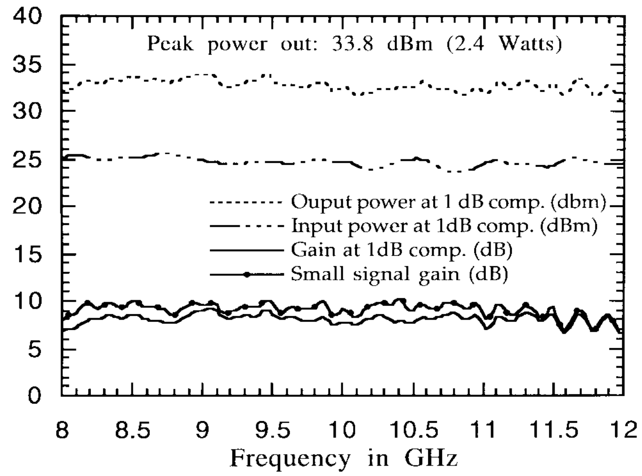

Fig. 3. Small and large signal results for 2 × 4 amplifier array.

Based on additional experimentation, only 0.5 dB of this loss is attributable to ohmic losses in the antennas; we believe that the remainder of the loss is due to a combination of a poor unbalanced slot-to-microstrip transition and poor contact between the antenna metallization and the waveguide walls. Both problems are currently under investigation to improve the insertion loss. We should note, however, that unlike conventional circuit combiner schemes, this insertion loss remains essentially constant as more devices or cards are added. The efficiency of corporate combiners (such as microstrip Wilkinson combiners) deteriorates quickly as the number of elements is increased [12]. Finally, the second harmonic at the output was 20 dB below the fundamental during large signal measurements and 30 dB below the fundamental for the small signal case.

IV. Conclusion

By using an array of tapered slotlines we have addressed the issue of bandwidth for spatial or quasioptical amplifiers. We have shown experimental results for 2 × 4 array of GaAs medium-power MMIC's at X-band. A 40% bandwidth covering the entire 8–12 GHz Band is observed with peak gain of 9.2 dB at 1 dB compression and peak output power of 2.4 W. The transitions from slotline to microstrip and packaging issues were found to degrade the combining efficiency of the circuit. Future implementations of the concept will focus on use of high-power devices for achieving competitive power levels, better transitions, and possibly using overmoded waveguides to accommodate more devices.

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