Spatial Power Combining for High-Power Transmitters

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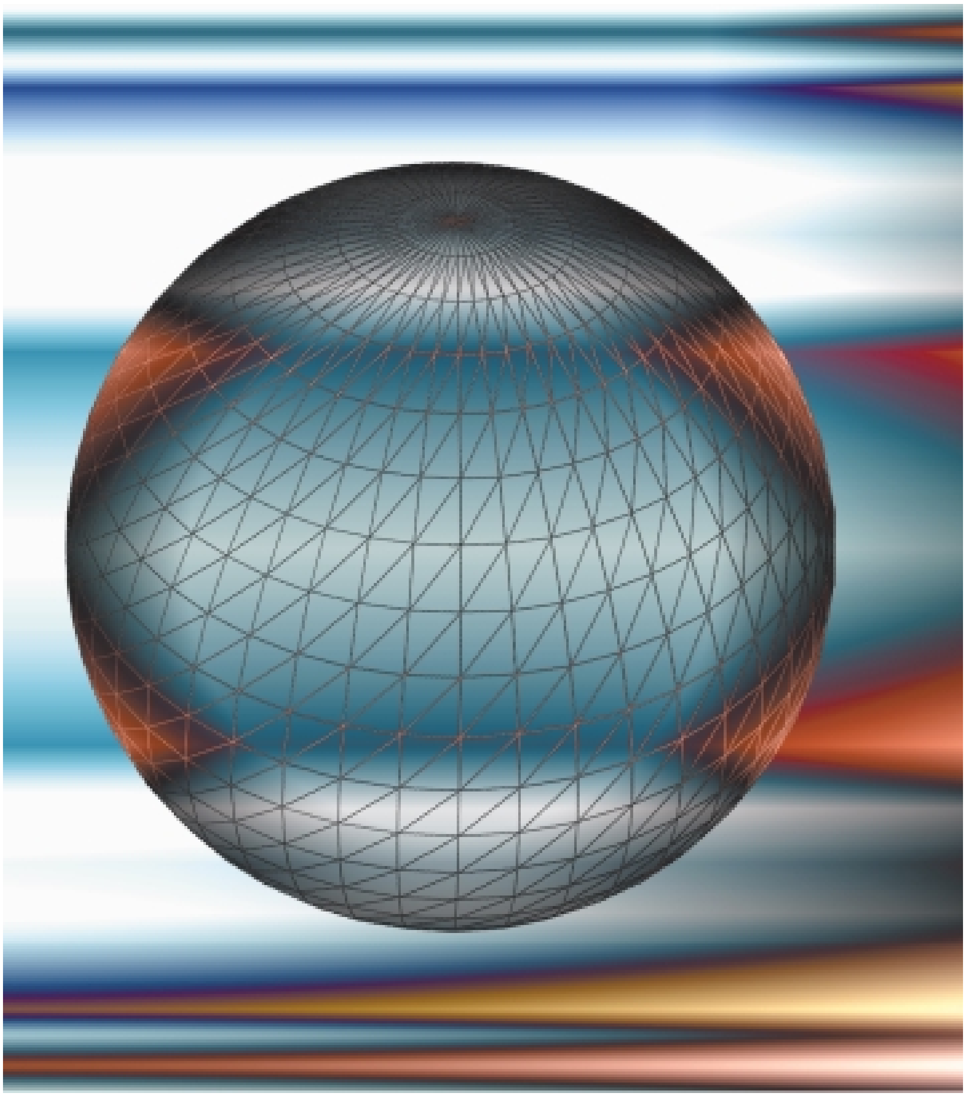

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As the operating frequency of semiconductor solid-state devices increases into the millimeter-wave region, the size of the devices and their power handling capability are reduced. In order to provide the advantages of a solid-state technology for moderate power levels at millimeter-wave frequencies, solid-state components must be combined. Spatial power combining provides enhanced RF efficiency by coupling the components to beams or modes in free space rather than via transmission lines in corporate combining structures. Recent in-

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vestment in research into these structures by government programs [1] has resulted in a number of successful demonstrations of spatial combined amplifier elements to reach useful power levels in frequency ranges from 10 GHz (150 W) to 60 GHz (36 W).

This article surveys recent progress in the development of high-power microwave and millimeter-wave solid-state sources using spatial power-combining techniques. Several promising topologies are discussed, and four compelling technology demonstrations are presented that have emerged from recent government-sponsored research in academia and industry. We also include a brief discussion of potential applications and systems insertion issues.

Power-Combining Concepts and Techniques

If components are combined using transmission line circuits, there is an upper limit to the number of elements (and, hence, a limit to the power that can be generated) due to transmission line and combining structure losses that depend on the number of elements in a nonlinear relation or due to the accumulating complexity of the circuit.

Figure 1 captures the concepts of corporate and spatial power combining. Figure 1(a) shows a circuit for a corporate combiner of power amplifiers integrated on a planar geometry. It can be seen that as additional elements are added the lengths of transmission line and the number of nodal combining circuits increase. The losses in the added line and combining circuits accumulate. They reduce and eventually kill the advantages of the combined power. Figure 2 shows the results of a path loss analysis of a corporate combining network, using Wilkinson combiners, for MMIC amplifiers at 10 GHz, 32 GHz, and 94 GHz. The analysis is based on optimized transmission lines for each frequency and experimental and scaled experimental measurements of passive circuit elements. The results are displayed with the output power (normalized to the output power of a single element) for the number of total amplifiers being combined. This data is inherently discrete; the curves drawn through the data points are only for the purpose of aiding visualization. Also drawn on the figure are lines representing constant 70% and 90% combining efficiency. Well-designed spatial power combining structures have combining efficiencies in this range, and the relatively small number of results indicate that the combining efficiency is constant with the number of elements combined, up to the physical limits of the architecture. From the figure, it is clear that for a small number of amplifier elements (and, hence, small levels of output power) planar corporate combining architectures are more efficient, but, as the number of amplifiers increases, it becomes necessary to use a spatially combined architecture. Also shown in Figure 2 is the effect of frequency on the losses. As frequency increases, the cross-over point where spatial combining becomes more efficient occurs at a smaller number of amplifier elements.

The field of spatial and quasi-optical (QO) power combining is still young, but experimental results are impressive and present an optimistic outlook for this technology

Spatially combined power sources can be implemented as arrays of oscillators or amplifiers. Oscillator arrays have been demonstrated, and these arrays have been shown to be capable of locking to an external ref-

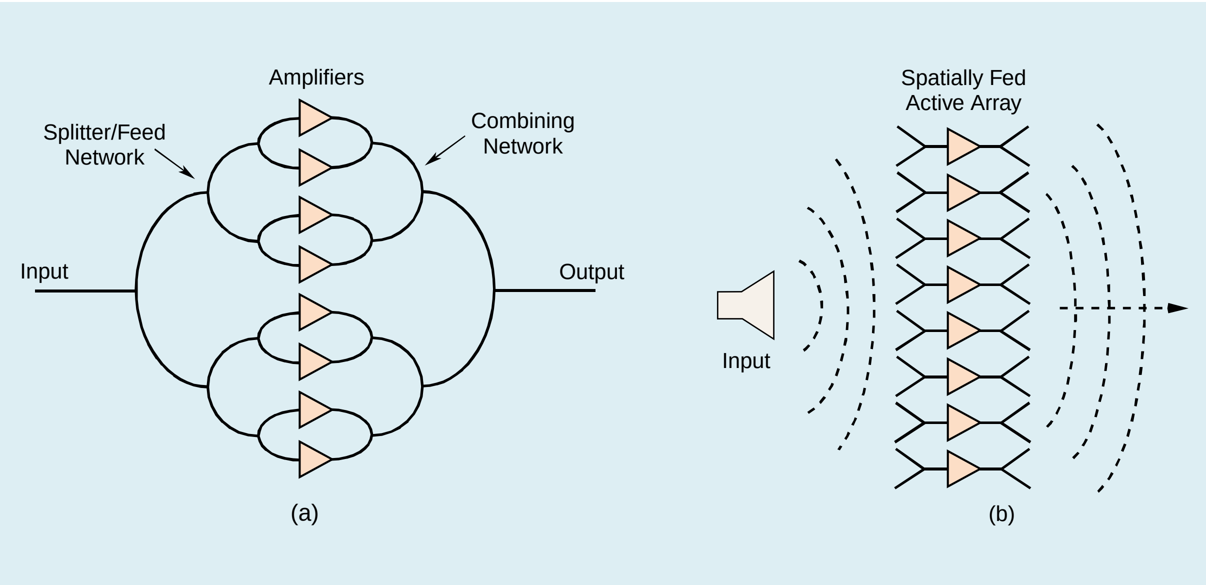

Figure 1. *(a) Conventional corporate combiner using binary Wilkinson spliter/combiner networks, (b) spatial combining architecture.*

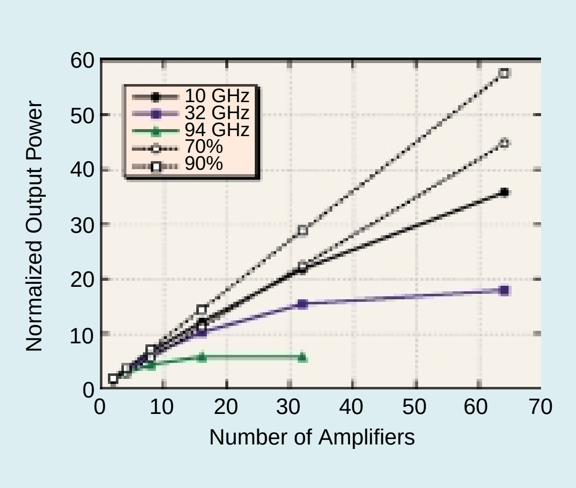

Figure 2. *Output power available from corporate and spatial power combining schemes versus the number of amplifier elements combined. Output power is normalized to the output power of a single element being combined.*

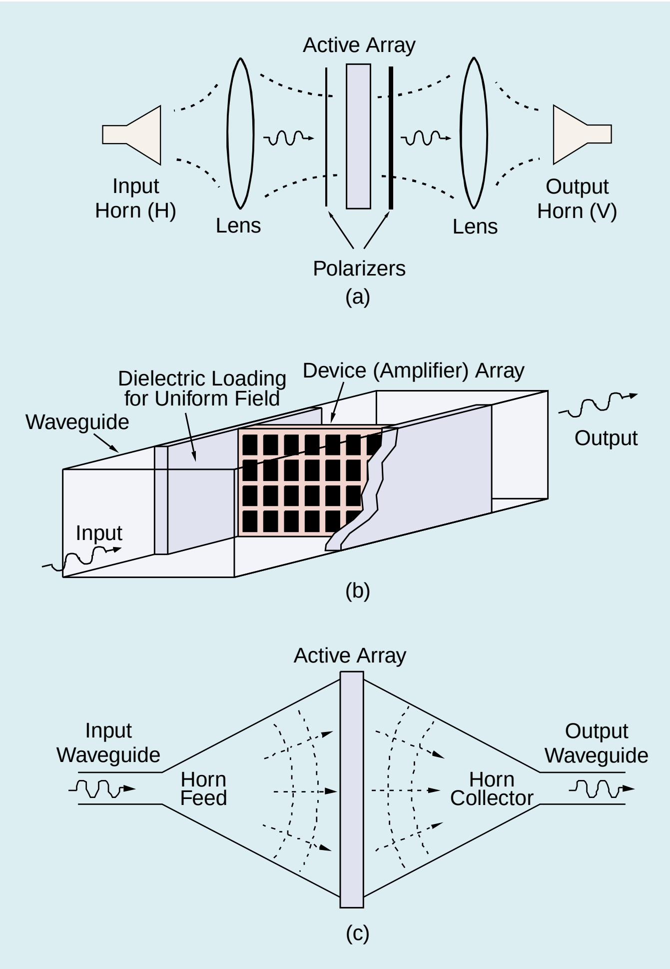

Figure 3. *(a) Quasi-optical beam amplifier concept using a lens-focused arrangement. Polarizers are useful when input and output beams are orthogonally polarized, (b) active array of amplifier elements inside of a waveguide, (c) active array in oversized waveguide with tapered horn feed to accommodate more amplifiers.*

erence signal or to a high Q external electromagnetic cavity. They have also demonstrated interesting beam-steering effects achieved by controlling the free running frequencies of oscillators on the edges of the array. Most of the immediate industrial and military interest, however, has focused on amplifier arrays because the generation of very low noise power is implemented in a straightforward manner by feeding the amplifiers with a controlled reference input signal. For this reason, this article will focus on amplifier array sources of microwave and millimeter wave power. Spatially combined arrays of other components, such as phase shifters, mixers, and frequency multipliers, have all demonstrated the potential to add significant functionality to a spatially combined component.

The experimental results discussed in a later section are impressive initial results and present an optimistic outlook for this technology. In addition, an extensive modeling and diagnostic capability has been developed, providing new tools to analyze design problems, to understand the basic physics of these highly coupled nonlinear circuits, and to transfer the knowledge to the general microwave design community in a usable manner. Predictive theoretical models of the stability [2], efficiency, and noise [3] in grid arrays and of the failure modes [4] and noise [5] in general spatial combining arrays have been formulated. With such complex interactions possible in these complicated electromagnetic structures densely packed with nonlinear devices and circuits, modeling has been a major factor in successful design and analysis. Features of the unit cell and subunit cell have been modeled using FDTD or commercial CAD routines, while a very comprehensive model including electromagnetic, nonlinear circuit, and transient thermal effects for large finite arrays has been developed [6]-[8]. This model, which is capable of simulating the nonlinear coupling effects and edge effects in the arrays, will eventually be publicly available over the Internet. These models have been well verified by experimental results, which gives confidence that much of the basic physics in these complex structures is understood. An electro-optic scanner has been developed, which can scan the vector EM field in the near field of an active array with extremely high resolution using nonperturbing fiberoptic probes. Such scans have been very helpful in understanding the complicated coupling effects and in diagnosing problems [9], [10]. Finally, three excellent reference books have been printed on the subject of spatial power combining [11]-[13]. So a broad array of high-performance tools and reference material is now available to assist in the design and analysis of these arrays.

Spatial Power Combined Amplifier Architectures

The term "spatial power combining" applies to structures that couple the components in free space. The term "quasi-optical power combining" is a subset of "spatial power combining." An early spatial combining architecture envisioned arrays of devices coupled to the electromagnetic field, with the RF field spatially controlled by lens and mirror elements, hence the term "quasi-optical" (QO). More recently, the term has been used for open array systems (whose RF field can be expanded approximately in summations of beam modes) even when there are no lenses or mirrors to confine the EM field. The term "spatial combining" is the more general term, and includes QO systems. It can be demonstrated [5] that the input losses associated with the distribution network do not fundamentally limit the combining efficiency and, hence, a spatially combined amplifier array can be fed either by a spatial feed, as shown in Figure 1(b), or by a corporate (circuit-based) feed, as shown in Figure 1(a). Such corporate-fed spatial combiners are discussed in [14], and are similar in design to classical antenna arrays with transmission-line feeds.

Figure 3 depicts several spatially combined configurations to control the RF EM field of space-fed active arrays. Figure 3(a) shows a QO system using lenses and polarizers to control the RF field. Similar configurations can use an open array with no lenses and may use phase control circuitry in each of the active antenna elements to provide beam control. Figure 3(b) portrays an active array inside a waveguide, where

The tray approach permits use of broadband traveling-wave antennas and improved functionality through circuit integration along the direction of propagation

the waveguide walls control the EM field and define its modal structure. Figure 3(c) presents a waveguiding structure controlling EM field, but expanding to allow a larger number of amplifier elements to be combined. The configurations shown collect the power output from the array into a waveguide, which is more convenient from a measurement and demonstration point of view. Such configurations could be used as direct replacements for other power sources, such as vacuum tubes, in the same basic system arrangement. However, if the overall system application requires radiating a beam into free space, then it may be advantageous to eliminate the power

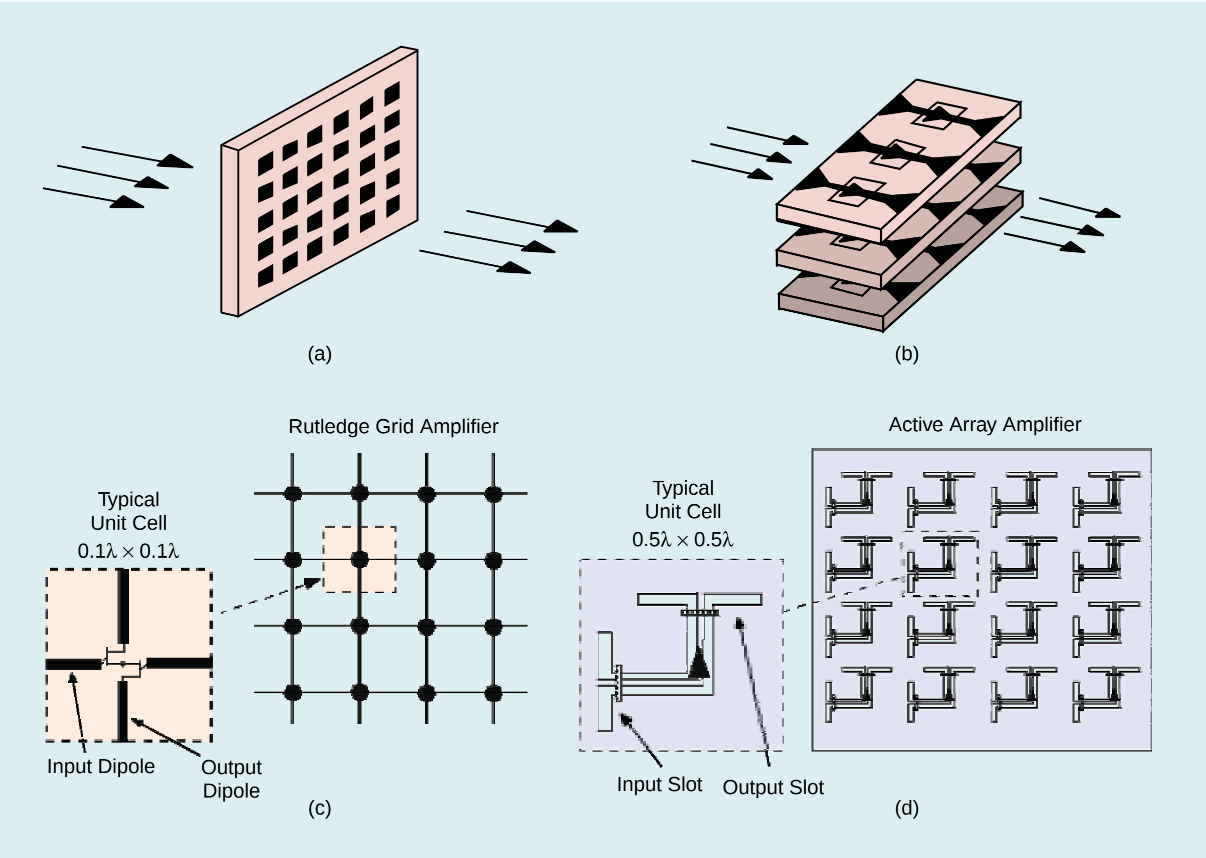

Figure 4. *(a) Tile and (b) tray array approaches. Spatial combiners using a tile approach have been constructed using either (c) a Rutledge grid or (d) conventional antenna array designs.*

collection side of the configuration and radiate directly from the active array. Phase-control and phase-shifting elements could be added to each active antenna element or a separate phase-shifting array could be cascaded with the active amplifier array [15], [16]. Mixer arrays [17] and frequency multiplier arrays [18], [19] have all been demonstrated as isolated components and have been proposed to provide additional functionality by cascading with an amplifier source array.

Active arrays for space-fed spatial or QO combining systems have been demonstrated in the two classic array topologies (tile and tray), shown in Figure 4(a-b). In the case of the tile approach, two distinct design approaches have been developed, shown in Figure 4 (c-d). In the Rutledge "grid" array of Figure 4(a), active devices are integrated at the vertical and horizontal intersections of a metallic mesh. The vertical wires connect either the input circuits or the output circuits of the amplifiers, while the horizontal wires connect the other circuit. An incoming wave can thus be polarized to interact only with the amplifiers' input circuits, while the outgoing wave will be orthogonally polarized. Polarizer grids used on either side of the grid array ensure isolation between input and output circuits. In the grid array, the active elements are generally spaced much closer than a half wavelength. The entire length of the grid wires acts as single antenna elements. In the active antenna array of Figure 4(d), separate antenna elements are integrated directly with active devices or an MMIC amplifier, with each element acting as an independent cell. The array acts as a periodic antenna array with the elements spaced at roughly half wavelength intervals. The EM wave is received on one side of the array, active devices can be placed on either or both sides of the array, and the array radiates on the other side. The antenna elements can be various combinations of patch and slot elements, with the possibility that in some configurations a common ground plane can isolate the input from the output. The tray ap-

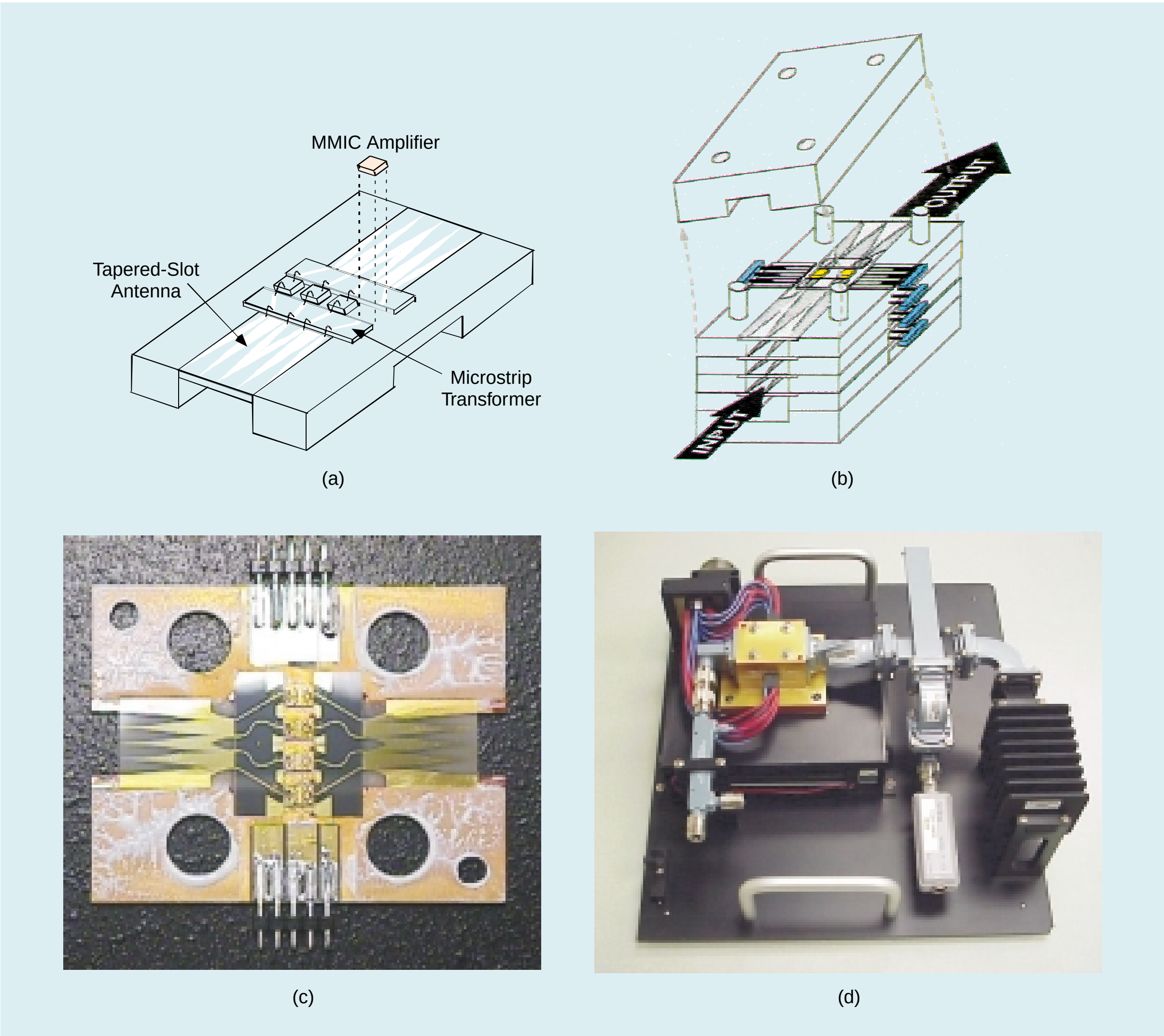

Figure 5. *(a) Individual tray showing finline or tapered-slot transitions and MMICs along with microstrip internnects, (b) assembled system with end caps, forming input and output waveguide apertures, (c) combiner circuit based on 2×4 arrays, (d) power measurements for the combiner circuit. Input power = 30 dBm.*

proach, illustrated in Figure 4(c), uses a tray of end-fire antenna elements with multiple trays stacked to provide a two-dimensional array. The tray then acts to receive an input signal to excite an electrical circuit that runs perpendicular to the plane of the antenna array, and to radiate from the other side of the trays. All of these topologies are represented in the section on experimental results.

The field of spatial and QO power combining is still too young for a clear determination of the advantages and disadvantages of the three topologies, however, some generalizations can be made. The grid architecture probably has the greatest sensitivity to the design of the dense structure of interacting active devices and antenna wires. It also provides the most straightforward approach to monolithic fabrication of an entire array. The grid structure is too dense to utilize off-the-shelf MMIC amplifier circuits, whereas the active antenna array and tray topologies can accommodate these large circuit elements. Because the tray architecture decouples the electrical circuit direction from the plane of the array, it has the most room for larger MMIC chips or other circuitry, such as phase shifters or frequency multipliers. The potential benefit to using MMIC chips is that advantage can be taken of the built-in isolation and stability in the MMIC chips. On the other hand, the individual device structure of the grid topology in principle provides the opportunity to optimize the circuit exactly for the conditions encountered in the grid. The tray architecture seems to provide the greatest isolation between active circuits. The tray architecture also facilitates the use of a backside metal fixture for thermal management, but some clever schemes have also been developed for thermal management using the tile approach, as described in the next section.

Experimental Demonstrations

Significant progress has been made in the laboratory development of solid-state spatial power combining under government sponsorship [1], resulting in multiple demonstrations of power modules in both industry and academia that can potentially challenge vacuum electronics in some applications. The results are too numerous to discuss exhaustively here. The following four demonstrations have been chosen to highlight some of the many promising results in each of the key design topologies.

UCSB 120 W X-Band Combiner

Researchers at the University of California, Santa Barbara have successfully implemented a spatial power combiner in a "tray" architecture [20], [21], as in Figure 5. The tray approach permits the use of broadband traveling-wave antennas [22] and improved functionality through circuit integration along the direction of propagation. Each tray (Figure 5(a), (c)) consists of a number of tapered slotline or finline transitions that coupled energy to and from a rectangular waveguide aperture to a set of MMIC amplifiers. The finline transitions rest over a notched opening in the metal carrier to which the MMIC are attached. When the trays are stacked vertically, as shown in Figure 5(b), the notched carriers form a rectangular waveguide aperture populated with the finline transitions. The use of the waveguide mode to distribute and collect energy to and from the set of amplifiers thus avoids loss mechanisms that would otherwise limit the efficiency in large corporate combiner structures.

In a planar tiled combiner system at Ka-band, input was coupled to the array through a waveguide port on the hard-horn feed, and the output power was radiated directly into space

An X-band module with six to eight trays, each containing four 5 W GaAs MMIC amplifiers (Figure 5(c)), was assembled onto a 19" rack-mounted assembly as shown in Figure 5(d), with a fan-cooled baseplate for

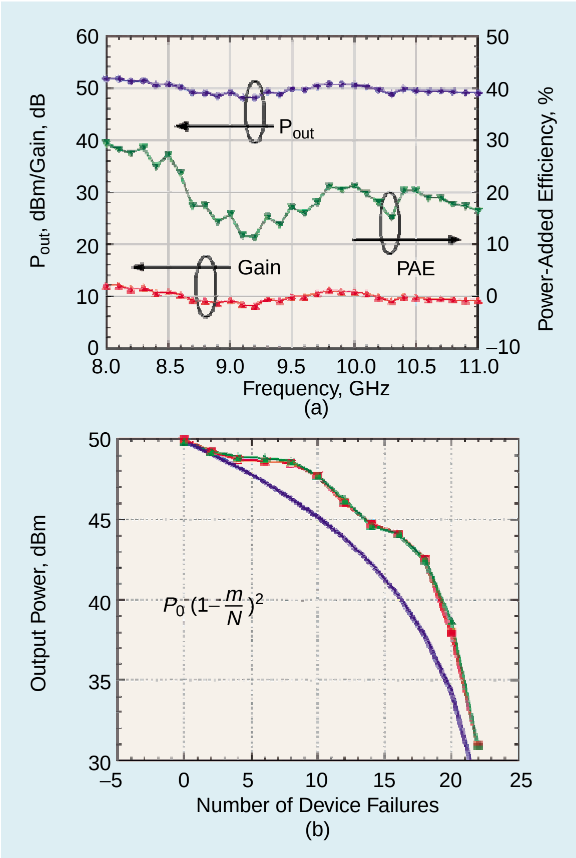

Figure 6. *(a) Measured output power (CW) and gain versus frequency for the 8×4 system, (b) graceful degradation characteristics for the 6×4 system.*

thermal management. Measured CW power-frequency response is shown in Figure 6(a) for the 32 MMIC (eight-tray) system. A maximum power of 150 W CW

Using the grid technique in which active devices are integrated into a dense metallic mesh, and the unit cell can be viewed as two orthogonally polarized dipole antennas connected by a differential amplifier

was measured at 8 GHz, at 8 V bias and total bias current of approximately 60 A. The measured graceful degradation characteristics for a similar 24-MMIC (six-tray) configuration is shown in Figure 6(b), along with the ideal trend that would be anticipated from power considerations alone [4]. The high power levels and broadband performance, along with the superb graceful degradation characteristics, make this topology an attractive alternative to low-power vacuum-tube sources such as MPMs [27].

Lockheed-Martin/NC State 25 W Ka-Band Array

Researchers at Lockheed Martin and North Carolina State University have recently demonstrated a planar 'tiled" combiner system at Ka-band (34 GHz) [23], [24]. This system used a 45-element, double-sided active patch antenna array with a hard-horn feed. The array, unit cells, and assembled combiner system are shown in Figure 7. In this case the input was coupled to the array through a waveguide port on the hard-horn feed, and the output power was radiated directly into space. This arrangement would find use as a feed structure for a large reflector antenna or lens-focused system. The hard-horn feed utilizes dielectric sidewall loading to create a uniform field profile [24], thus insuring equal drive power to the array elements. The MMIC amplifiers rest directly on a thick central ground plane through

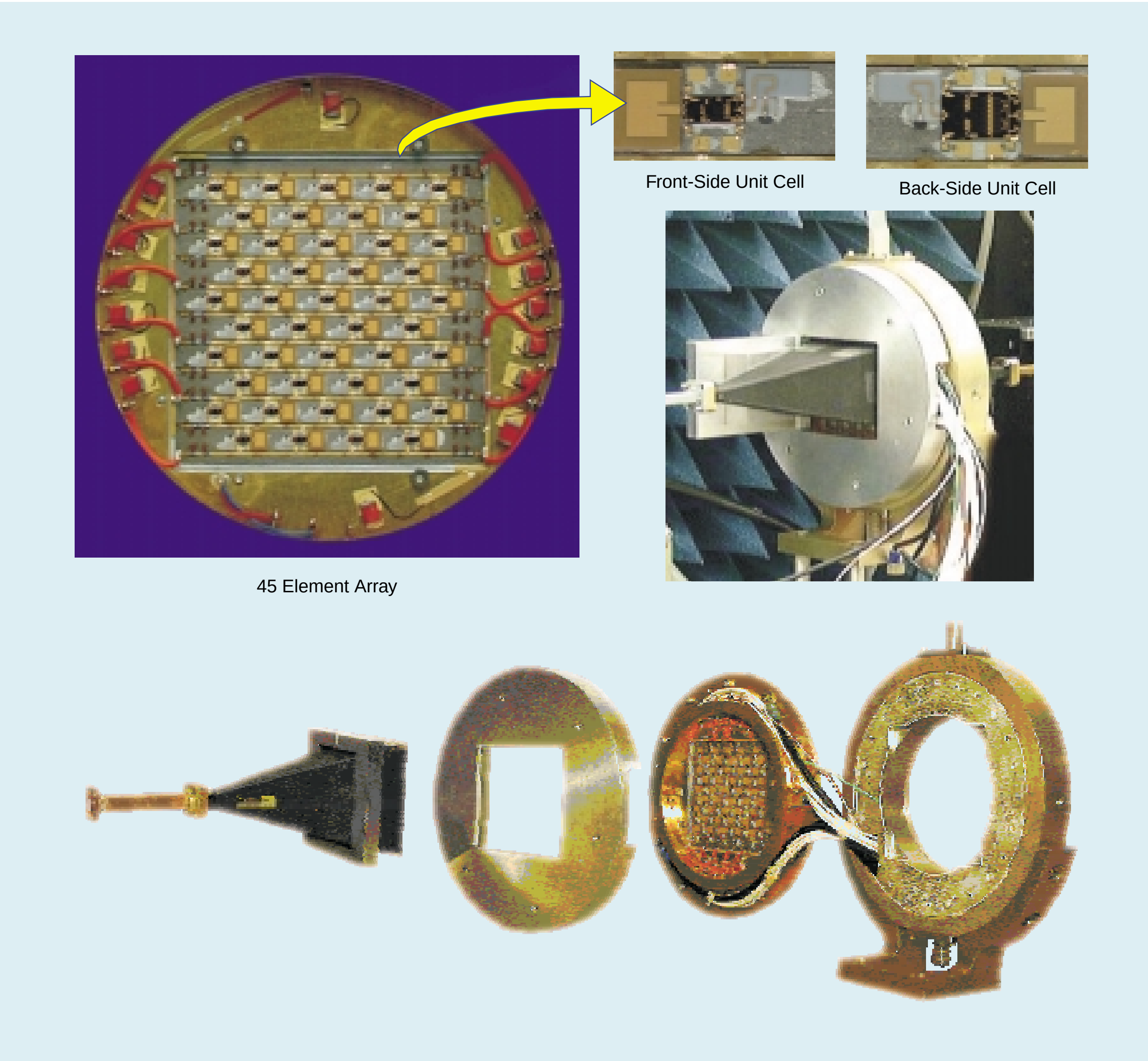

Figure 7. *Lockheed-Martin/NCState 45 element array producing 25 W at Ka-band.*

which the signal is coupled via integrated coaxial vias. This thick ground provides good input/ output isolation, and allows for excellent thermal management. This particular system included a liquid- cooled baseplate.

Measured results for the Lockheed-Martin/ NC State system are shown in Figure 8. Based on measurements of the radiation pattern and effective isotropic radiated power (EIRP) of the array, a radiated power of 44 dBm (25 W) was recorded at 34 GHz, with a 3 dB bandwidth of 800 MHz. The array had a small-signal gain of 10 dB at this frequency, and the power measurements were made at 3 dB gain compression.

Caltech/Rockwell 5 W 37 GHz Grid

Researchers at Caltech have developed a unique approach to QO power amplification using the so-called "grid" technique, where the active devices are integrated into a dense metallic mesh. The unit cell can be viewed as two orthogonally polarized dipole antennas, connected by a differential amplifier. The grid topology is shown in Figure 9. The single-sided grid is fabricated monolithically on a GaAs substrate, and mounted on an aluminum notride heat spreader for good thermal management. Polarizers are used to couple the input and output signals to and from the grid, which is intended for use in a Gaussian beam system like that of Figure 3(a).

The most recent demonstration at Caltech uses a grid with 512 pHEMT transistors. A close-up of a portion of this grid is shown in Figure 7. The total die area is 1 cm^2. Measured small-signal frequency response and power saturation characteristics are shown in Figure 10. A maximum gain of 8 dB was recorded at 37 GHz, with a 1.3 GHz (3.5%) bandwidth. The array generated 5 W CW output power at 3 dB gain compression, with a 17% power-added efficiency (2.7 V @ 6.5 A). The Caltech group also measured a third-order intercept point of 45 dBm for this amplifier. An output combining loss of 1 dB was estimated from the measurements, indicating a combining efficiency of ~80%.

Sanders 35 W 61 GHz Combiner

Arguably the most stunning accomplishment in spatial combiners was recently reported by researchers at Sanders [26], who described a combiner with 272 MMICs in operation simultaneously. This system is depicted in Figure 11. This system used a sectoral horn feed to a 19-element linear dipole array. Each dipole then coupled energy to a tray containing 16 three-stage MMIC output amplifiers with 20 driver MMICs. The output signal from the 19 × 16 output dipole array network was collected using a pyramidal horn. This array reportedly generated 35 W CW output power at 61 GHz, with 60 dB of small-signal gain and a 4 GHz bandwidth. A 1 °/dB AM-PM distortion was reported.

Large Signal Performance and Linearity

With the achievement of single-mode output power levels exceeding 100 W at X band and 10 W at Ka band, QO amplifiers have advanced to a point where they can compete on equal terms with vacuum tube amplifiers, particularly the microwave power module (MPM). The

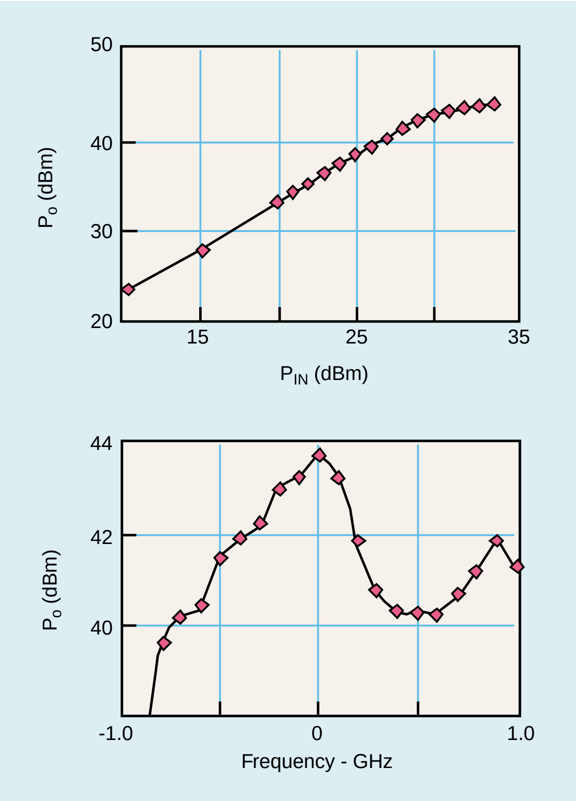

Figure 8. *Measured AM-AM and frequency response curves for the Lockheed-Martin/NCState amplifier in Figure 7.*

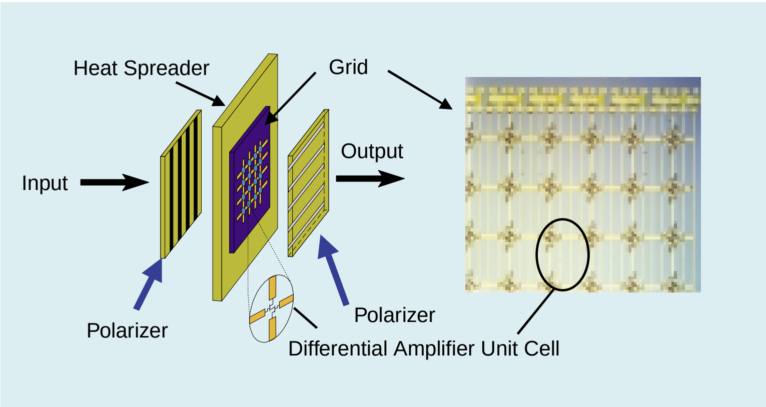

Figure 9. *Caltech grid amplifier system [25].*

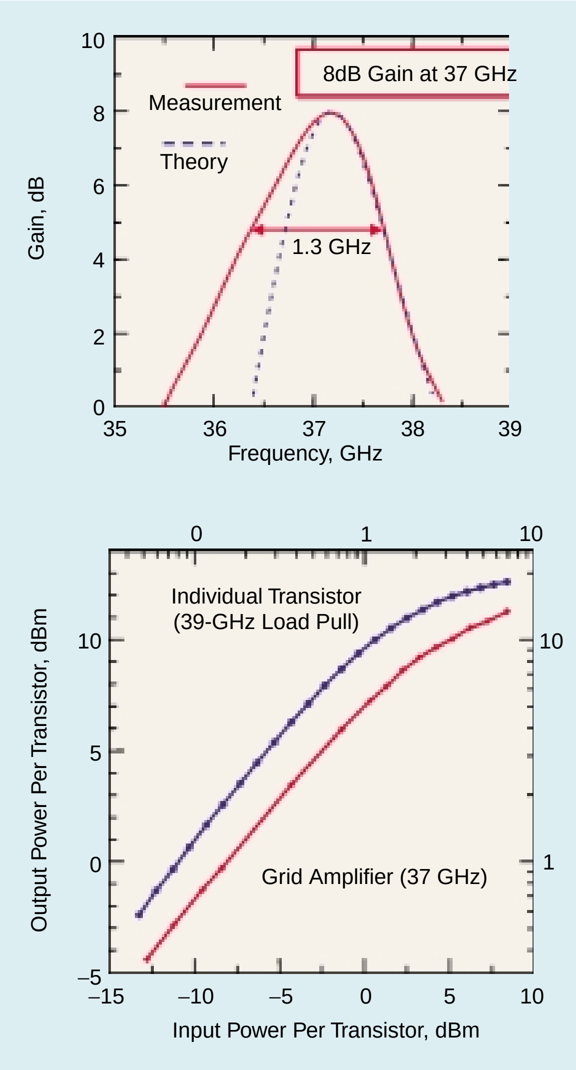

Figure 10. *Measured response for the grid amplifier of Figure 9 [25].*

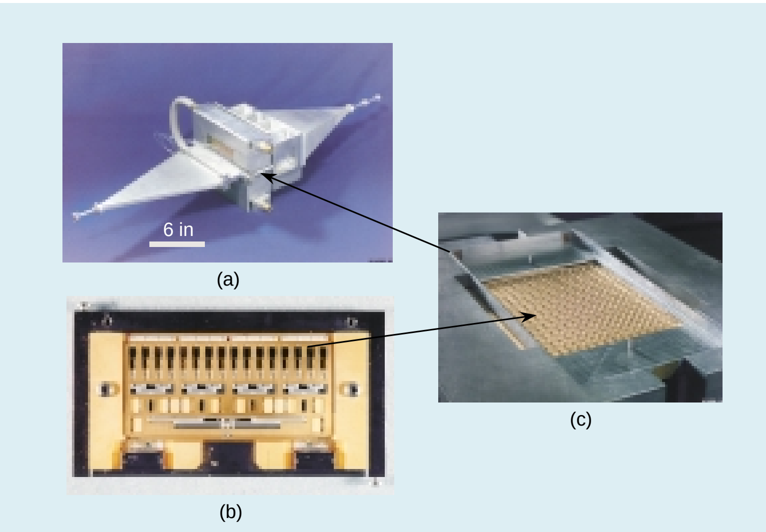

Figure 11. *Spatial combiner developed by Sanders [26]. (A) Power amplifier assembly, (b) tray module containing 16 output MMIC three-stage power amplifiers with 20 driver chips, (c) 304 dipole radiating elements fed by 19 tray modules.*

MPM is the elegant combination of a solid-state exciter and traveling-wave tube (TWT) amplifier that over the past decade has set records for power-bandwidth product in the microwave and millimeter-wave bands, and has substantially lowered the noise floor compared to conventional TWTs [27].

To contrast the large-signal capabilities of QO amplifiers and MPMs, it is important to address not only the issues of output power and efficiency, but also linearity and intermodulation distortion. Shown in Figure 12 are curve fits to the large-signal amplifier characteristics of the recent Caltech/Rockwell Ka-band QO grid amplifier at 37 GHz in comparison with curve fits to MPM characteristics [28] at the same frequency. The top curve for each amplifier represents the single- tone output power versus input power, showing constant gain at low input and saturation behavior higher up. The bottom curve represents the output power of the third-order intermodulation products (at frequencies $2w_1 - w_2$ and $2w_2 - w_1$) versus the input power of each of two equal-amplitude tones at w_1 and w_2, respectively, both within the passband of the amplifier. The curve fits are based on a cubic Volterra-series representation for the amplifier transfer characteristic, $v_{out} = a_1 v_{in} + a_3 (v_{in})^3$ [29]. The coefficients are calculated from the small-signal power gain (G) and the saturated output power (P_{sat}) of each amplifier, and are found to be $a_1 = 100$ and $a_3 = -124.6$ for the MPM having $G = 40$ dB and $P_{sat} = +42$ dBm, and $a_1 = 2.51$, $a_3 = -0.0067$ for the QO amplifier having $G = 8$ dB and $P_{sat} = +37$ dBm.

A useful parameter that results from this analysis is the third-order intercept point, IP3, i.e., the level at which the linearly projected single-tone output and one of the third-order intermodulation products become equal at the same input power. From the third-order Volterra analysis, one finds IP3 = $2(a_1)^3/3a_3Z0$, where $Z0$ is the load characteristic impedance (assumed equal to the source impedance). This evaluates to +50 dBm and +45 dBm for the MPM and QO amplifiers, respectively. In other words, the Ka-band QO amplifier is within 5 dB of the MPM in saturated output power and IP3.

Although IP3 is an extrapolated parameter that can never be reached in practice, it facilitates an important measure of the linearity of an RF system called the spur-free dynamic range (SFDR). The SFDR represents the ability of a system to detect or boost signals in the presence of both noise and other strong signals, and is relevant to several system applications such as transponding the multiple carriers that routinely pass through terrestrial base stations operating under code-division multiple access (CDMA). A second example is the detection of a frequency-chirped radar return signal in the presence of strong clutter. The lower limit of SFDR occurs, as in most measures of linearity, when the input signal power equals the noise power. To account for multiple strong input signals, the upper limit of SFDR is defined to occur when a single output third-order intermodulation product equals the output noise power. These lead to the well-known expression SFDR = $[IP3/(NF*G*B)]^{2/3}$ where NF is the overall noise factor, G is the overall gain, and B is the instantaneous bandwidth [30].

Although the noise figure has not yet been measured on the given amplifier or any other QO amplifier having > 1 W output power, there is good reason to believe that it will be significantly lower than that of each individual transistor or amplifier making up the array [5]. This is because the phase noise from the individual amplifiers is uncorrelated, but the signals add coherently with little additional noise if the output power combining efficiency is suitably low. Typically the noise figure of RFIC or transistor amplifiers used in QO amplifiers is 6 dB or less, so that the overall NF of an efficient device should be roughly 3 dB or less. This is to be contrasted to an NF of at least 10 dB in MPM amplifiers operating in Ka band [28].

The lower noise figure would appear to counteract the inferior IP3 of a QO amplfier to make it, at best, competitive to MPMs in terms of SFDR. However, to make the comparison meaningful, the gain term in the above expression must be set to the overall system gain, including preamplifiers ahead of the MPM and QO amplifiers to bring the overall gain to typical levels of 60 dB or more. For an MPM operating in a transponder, this would likely be a solid-state low-noise amplifier (LNA) having excellent noise figure but low IP3 and SFDR. Hence, linearization techniques would have to be applied in the amplifier chain to achieve high overall SFDR. This is a common practice in any transponder (e.g., satellite or base station) handling multiple carriers in each amplifier.

The low-noise figure of a QO amplifier opens up the possibility of a new architecture in which preamplification is done with an identical QO amplifier. In other words, the QO amplifier plays the dual role of LNA and SSPA. This means that useful system gains may be achieved with much less linearization. From a practical standpoint, a cascade of QO amplifiers is feasible because the difficult task of illuminating a QO array with a quasi-plane wave only needs to be done at the first stage. The output wave of each QO amplifier should have a form well suited to efficiently driving the next stage. An estimate of the system level can be made using the above formula for SFDR along with the derived IP3 of +43 dBm, a noise factor of 2, a gain of 8 dB, and an instantaneous bandwidth of 100 MHz. The resulting SFDR is found to be 85 dB. This is deceptively large because with a gain of only 8 dB the overall noise figure and IP3 will be degraded by the following QO stages. An analysis of the QO-amplifier cascade is presently underway [31].

A combiner with 272 MMICs in operation simultaneously reportedly generated 35 W CW output power at 61 GHz with 60 dB of small-signal gain and a 4 GHz bandwidth

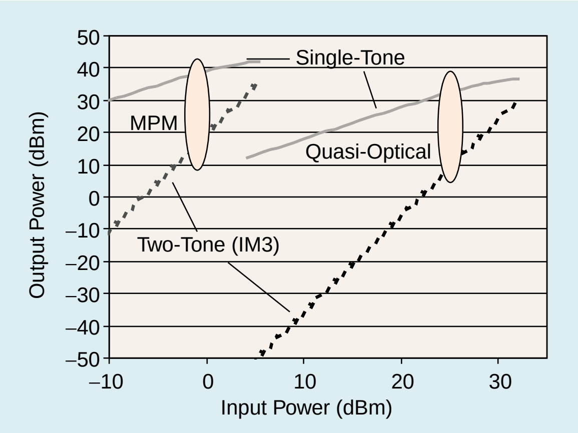

Figure 12. *Comparison of power saturation characteristics for MPMs and a quasi-optical grid, showing both fundamental and third-order product from a two-tone measurement.*

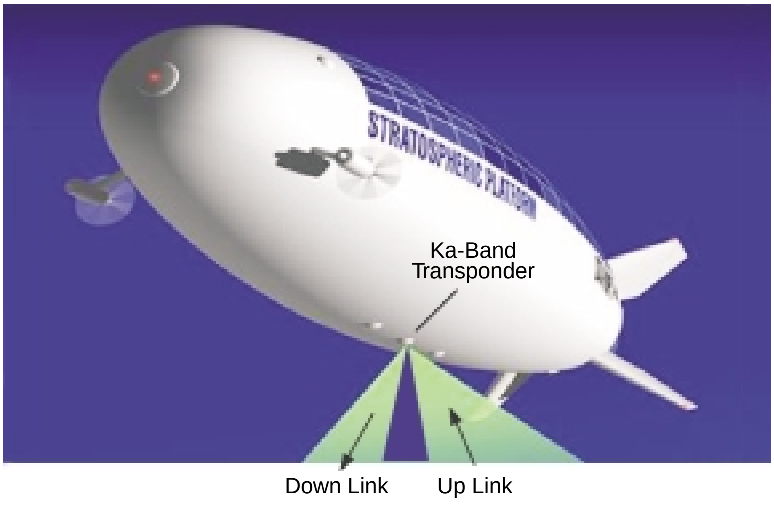

Figure 13. *Possible next-generation communications node on an Aerostat (blimp).*

Applications

Given the comparable power handling and linearity of QO amplifiers relative to MPMs, the QO devices may soon compete in replacing TWT amplifiers in many of the communications applications where tubes have practically become a sole source. For example, in Ka-band satellite transponders the tube must transmit up to about 50 W cw spread over several carriers in a variety of different access schemes (e.g., CDMA) and modulation formats (e.g., QPSK, etc.). And it must do this in the harsh environment of space where thermal management is difficult (and expensive) and ionizing radiation is potentially harmful to the QO arrays. The relative ruggedness of vacuum-tube devices in this environment may favor the MPMs in this application [32].

A more promising application for the QO amplifiers, particularly the QO cascade architecture discussed above, may be on airborne communication transponders. Aerostats, such as the one depicted in Figure 13, are presently being pursued in the military and commercial sectors alike because of their low cost, relatively simple deployment, and far shorter range between ground stations and the air platform. Much discussion has focused on aerostats as the enabler for local multipoint distribution services (LMDS) in Ka band between 28 and 31 GHz. This is a band rich in available spectrum but fraught with propagation losses in terrestrial links and transmit-power shortcomings in satellite links. Our preliminary analysis on this application shows that satisfactory levels of bit-error rate and link margin will be possible with a multistage QO transponder in which the final-stage QO transmit amplifier is operating at an output of +33 dBm.

A second application of interest for military purposes is a QO transceiver in a Ka-band monostatic missile seeker. Historically several approaches have been pursued for a mm-wave seeker because of its all-weather capability and potential precision. But to our knowledge only one of these (AMRAAM) has made it to production. Infrared, laser, and GPS guidance have become more popular, largely because of their significantly lower cost and relatively simple construction. This situation would change if, through new architecture, QO technology could provide more functionality that would reduce the cost and complexity of mm-wave missile seekers. Given the present discussion on linearity and noise figure, an interesting QO architecture for seekers would have a cascade of QO amplifiers, each one designed to be reciprocal. In fact, an architecture of this type has already been demonstrated at X band using back-to-back transistor amplifiers in each cell and orthogonal linear antennas for polarization discrimination between the transmitted and received signals [32].

To add further functionality, a passive QO device could be added as the last stage of the chain to provide beam steering and forming. Several different beam- steering architectures have been proposed or investigated, most consisting essentially of a two-dim array of phase shifters or switches coupled to input and output waveguides or planar antennas [34]. The key point here is that a QO beam steerer is compatible with the QO amplifier cascade and eliminates the need for a mechanical gimbal, the long-standing beam-steering component in RF-guided seekers. Not only are gimbals expensive, but they occupy a significant fraction of the missile volume (5" diameter). Furthermore, some degree of beam-forming function would allow the steering array to act like an antenna, thereby eliminating another cumbersome component in seeker front ends, the parabolic dish antena. Lacking the gimbal and dish, it is conceivable that a QO seeker could have roughly 50% lower size, weight, and cost.

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