Spatial Power Combining Amplifier for Ground and Flight Applications

Jose E. Velazco* and Mark Taylor*

ABSTRACT. — Vacuum-tube amplifiers such as klystrons and traveling-wave tubes are the workhorses of high-power microwave radiation generation. At JPL, vacuum tubes are extensively used in ground and flight missions for radar and communications. Vacuum tubes use electron beams as the source of energy to achieve microwave power amplification. Such electron beams operate at high kinetic energies and thus require high voltages to function. In addition, vacuum tubes use compact cavity and waveguide structures that hold very intense radio frequency (RF) fields inside. As the operational frequency is increased, the dimensions of these RF structures become increasingly smaller. As power levels and operational frequencies are increased, the highly intense RF fields inside of the tubes' structures tend to arc and create RF breakdown. In the case of very high-power klystrons, electron interception — also known as body current — can produce thermal runaway of the cavities that could lead to the destruction of the tube. The high voltages needed to power vacuum tubes tend to require complicated and cumbersome power supplies. Consequently, although vacuum tubes provide unmatched high-power microwaves, they tend to arc, suffer from thermal issues, and require failure-prone high-voltage power supplies. In this article, we present a new concept for generating high-power microwaves that we refer to as the Spatial Power Combining Amplifier (SPCA). The SPCA is very compact, requires simpler, lower-voltage power supplies, and uses a unique power-combining scheme wherein power from solid-state amplifiers is coherently combined. It is a two-port amplifier and can be used inline as any conventional two-port amplifier. It can deliver its output power to a coaxial line, a waveguide, a feed, or to any microwave load. A key feature of this new scheme is the use of higher-order-mode microwave structures to spatially divide and combine power. Such higher-order-mode structures have considerably larger cross-sections than comparable klystrons and traveling-wave tube counterparts and thus avoid RF breakdown and thermal issues common to vacuum tubes. We present a basic description of the SPCA mechanism and initial results of an S-band (2.4 GHz) 100-W, 45-dB gain SPCA prototype. We also discuss future X-band (8.4 GHz), Ka-band (32 GHz), and W-band (94 GHz) SPCA designs for both radar and communications applications.

I. Introduction

The generation of high-power microwave radiation is a difficult technical dare that is typically limited by, among other things, the stresses posed by very high-power densities produced by intense microwave fields. Such stress may lead to radio frequency (RF) break-down and destructive thermal issues. Vacuum-tube amplifiers such as klystrons and traveling-wave tubes have been the workhorses for generating the desired high power output. In NASA's Deep Space Network (DSN), S-band (2025–2120 MHz) and X-band (7145–7190 MHz) uplink communications with spacecraft are achieved via multikilowatt klystron amplifiers. These high average power klystrons are used by several Deep Space Stations (DSSs) to provide data uplink for numerous deep-space missions. Klystrons are currently installed in DSN 70-m and 34-m antennas.[1] Over the past years, these vacuum devices have suffered from arcing and RF breakdown issues and have the potential to become single-point-failure items that could preclude communications with spacecraft, and eventually could force the shutdown of the entire DSS. Consequently, there is a clear need to find a suitable and reliable replacement for these amplifiers in order to prevent uplink failure, reduce maintenance costs, and minimize downtime of the stations furnished with these klystrons.

NASA's Goldstone Solar System Radar (GSSR) uses two 250-kW klystrons to generate high-power X-band (8.4 GHz) signals for imaging of asteroid and planetary surfaces in the solar system.[2] Due to the high-power operation required by the GSSR, these klystron tubes are pushed to their limits. The high-power densities existing inside the tube envelope generate severe thermal issues that can consequently translate into tube failure and poor reliability. For example, over the past 10 years there has been an average failure rate of one klystron tube per year.

In addition, flight mission transmitters use microwave tubes, such as traveling-wave tubes and extended interaction klystrons (EIKs), for both radar and communications that also could become single-point-failure items that can jeopardize mission success. Missions that currently use or plan to use EIKs include CloudSat, EarthCare, and Surface Water and Ocean Topography (SWOT).

In the civilian and military arenas, high-power tube microwave amplifiers such as klystrons and traveling-wave tubes are commonly used in phase array radar, communications, electron accelerators, and microwave heating of ceramics and materials, among others. These tubes are expensive, typically require high voltages and, as stated earlier, can also become a single point of failure.

In building the transmitter of the future, there is a need for microwave tube amplifier alternatives that are smaller, lighter in weight, more reliable, and have higher power, especially for ground and flight radar and communication applications.

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[1] *C, S/X-band 20 kW Transmitter (70 m) O&M Manual*, DSN No. 867-000017 (internal document), Jet Propulsion Laboratory, Pasadena, California.

[2] GSSR system description — http://gssr.jpl.nasa.gov/gssr.system.html#Transmitters

In this article, we present a new concept for the amplification of coherent microwave radiation we are calling the Spatial Power Combining Amplifier (SPCA).[3] For amplification of microwave signals, the SPCA encompasses the use of a waveguide/cavity structure to first spatially divide microwave power, then amplify the resulting signal using state-of-the-art amplifiers — such as solid-state monolithic microwave integrated circuits (MMICs) — and lastly, to spatially combine the resulting amplified signals. Competing power-combining technologies use devices such as microstrip and coaxial power combining structures, which suffer from destructive thermal issues (hotspots) due to high-power densities imposed on the material by the high-power microwave signals. Because the SPCA uses space (air) for coherently combining microwave signals, which greatly reduces power density and thermal issues, we envision very high power operation of these devices. Two other key features of the SPCA are its compactness and low operating voltages (e.g., 28 V).

We present a general description of the SPCA and provide a power analysis at various SPCA stages. We also present preliminary results of an S-band 100-W SPCA prototype.

II. General Description of the SPCA

Figure 1 shows a general schematic of the SPCA. The SPCA components include a signal generator (SG), a spatial power divider (SPD) structure, coupling mechanisms (CMs), amplifiers (Amps), a spatial power combining (SPC) structure, and a load.
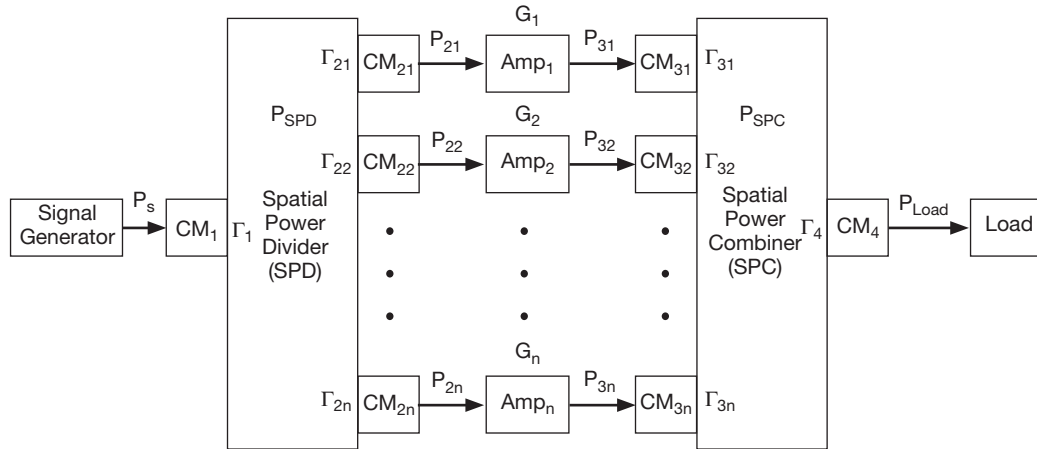

Figure 1. Schematic showing various parts of the SPCA amplifier.

In the current SPCA embodiment, the SPD and SPC are transmission-line structures that can hold various types of electromagnetic modes that include transverse electromagnetic (TEM), transverse-electric (TE), transverse-magnetic (TM), and others. The transmission-line structures (SPD/SPC) that hold these modes are conducting structures that can be hollow (air-filled) or could be loaded (filled/lined) with a suitable material of permittivity ε and permeability μ. Examples of these transmission line structures include rectangular, square, annular, and circular waveguides; rectangular, square, annular, coaxial, and circular cavity resonators, etc.

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[3] J. E. Velazco, "Spatial Power Combining Mechanism for the Generation and Amplification of Electromagnetic Radiation," JPL NTR 50016, Provisional Patent CIT File No.: CIT-7505-P.

The input signal provided by the SG could be any type of microwave signal that needs to be boosted and could be provided by a signal generator, oscillator, antenna, preamplifier, another SPCA, etc.

The coupling mechanisms (CMs) are structures that allow for remotion/injection of microwave signals from/to the SDP and SPC, respectively. Specifically, in the SPCA the CMs allow for:

- Feeding microwave power from the SG into the SPD.

- Extraction of the microwave power from the SPD for subsequent amplification by the Amps.

- Injection of the amplified power into the SPC.

- Extraction of the microwave power from the SPC for delivery to the load.

Examples of CMs include, but are not limited to, coupling irises, mode converters, magnetic loops, electric capacitive probes, wideband antennas, any other type of antenna, etc.

Amps are any type of mechanism that can amplify microwave signals and provide a gain G. In this application, Amps are solid-state MMIC amplifiers. Another CM is employed to deliver the power inside the SPCs to the load. The load could be another SPCA, an antenna, a waveguide, a charged-particle accelerator, a cavity, or any other device requiring high-power microwave radiation.

The SPCA can be designed to possess the following features:

- Narrowband operation (using cavity resonator structures).

- Wideband operation (using waveguide structures or coupled cavities).

- Linear/circular polarization (using symmetric/asymmetric TE/TM modes).

The SPCA gain is dictated by the gain value provided by one Amp. Several SPCAs can also be arranged in tandem to increase the overall gain of the resulting device.

Next we provide a general discussion of microwave power transmission along the SPCA.

III. SPCA Microwave Power Analysis

Figure 1 shows the flow of microwave power along the SPCA. P_S is the power delivered by the signal generator; P_{SPD} and P_{SPC} are, respectively, the microwave power inside the SPD and SPC. P_L is the power delivered to the load.

As shown in Figure 1, when power is fed into the SPD, it is evenly split n-ways and extracted via the coupling mechanisms CM_{2i} ($i = 1, 2.., n$). (Here, n is the number of amplifiers and coupling mechanisms used.) Power extracted from the SPD is amplified by a series of identical phased-matched solid-state amplifiers. The amplified power is fed into the SPC via additional coupling mechanisms CM_{3i}. High-power microwaves are generated inside the SPC

by coherently spatial combining the power delivered by the Amps via coupling mechanisms CM_{3i}. The CM_4 allows for efficient delivery of the high-power microwaves to the load.

The value of microwave power along the various SPCA stages is given by (see Figure 1):

$$P_{SPD} = \Gamma_1 P_S$$

$$P_{21} = \Gamma_1 \frac{P_S}{n} \Gamma_{21} \quad P_{31} = \Gamma_{31} P_{21} G_1$$
$$P_{22} = \Gamma_1 \frac{P_S}{n} \Gamma_{22} \quad P_{32} = \Gamma_{32} P_{22} G_2$$
$$\cdot \qquad\qquad \cdot$$
$$\cdot \qquad\qquad \cdot$$
$$P_{2n} = \Gamma_1 \frac{P_S}{n} \Gamma_{2n} \quad P_{3n} = \Gamma_{3n} P_{2n} G_n$$

(1)

where Γ denotes the coupling coefficient of the coupling mechanisms. This coefficient is an indicator of the level of impedance matching between adjacent microwave structures and is a qualifying coefficient of how efficiently power is transferred between them. For the SPCA application, Γ values are typically ≈ 1.

Conservation of power inside the SPD dictates that

$$\Gamma_1 P_S = \Gamma_1 \frac{P_S}{n} \sum_{i=1}^{n} \Gamma_{2i} + P_R$$

(2)

where P_R is the microwave power that remains inside the SPD structure. Equation (2) simply states that the power extracted from the SPD structure is equal to the injected power minus the power remaining in the SPD (which is typically very small, i.e., $P_R \approx 0$ if $\Gamma_{2i} \approx 1$ for all values of i).

All the signals that are extracted from the SPD are amplified by the Amps by a factor of G. The amplified signals are subsequently injected into the SPC via their respective CMs. CM_{3i} has a corresponding coupling factor Γ_{3i} , where $i = 1, 2.., n$.

In general, for n number of Amps and CMs, the total output power inside the SPC, P_{SPC}, is given by

$$P_{SPC} = \Gamma_1 G \frac{P_S}{n} \sum_{i=1}^{n} \Gamma_{2i} \Gamma_{3i}$$

(3)

and

$$P_{Load} = \Gamma_4 P_{SPC}$$

(4)

where $G = G_1 = G_2 .. = G_n$ has been assumed.

Note that when all the coupling mechanisms are critically coupled, i.e., $\Gamma_1 = \Gamma_{ki} = 1$ (where $k = 2, 3$ and $i = 1, 2.., n$), we obtain

$$P_{SPC} = P_S G.$$

(5)

In addition, if we denote the maximum power output of each Amp, P_{Amp}^{max}, as

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$$P_{Amp}^{max} = P_{31}^{max} = P_{32}^{max} = \cdots P_{3n}^{max}$$

then Equation (3) can be expressed as

$$P_{SPC} = \sum_{i=1}^{n} P_{3i}^{max} = nP_{Amp}^{max} \qquad (6)$$

where $\Gamma_{3i} = 1$ has been assumed (for $i = 1, 2.., n$). Equation (5) states that the total gain of the SPCA is provided by the gain G of the Amps. However, the maximum SPCA output power, given by Equation (6), is equal to n times the maximum power provided by one Amp. Note here that from Equation (3) we obtain

$$P_{Amp}^{max} = G\frac{P_S}{n}$$

where we have assumed that $\Gamma_1 = \Gamma_{2i} = \Gamma_{3i} = 1$, ($i = 1, 2.., n$). Recall that the main objective of the SPCA is to amplify the input microwave signal (P_S). In order to produce a large amount of power (beyond the power produced by a single Amp), it is required that $n \gg 1$. Thus, from Equation (6), in order to considerably boost the microwave input signal, several Amps (as well as several CM$_2$s and CM$_3$s) will be required. This poses a challenging demand on space along the SPCA structure. Consequently, for the SPCA to deliver sizeable amounts of microwave output power, the SPD and SPC structures must be dimensioned in such a way so as to allow the implementation of several CMs/Amps. It is envisioned that values of n can vary from 2 to 100 and beyond.

IV. Electromagnetic Mode Selection

In order to achieve high output power, the SPCA mechanism requires suitable microwave operating modes that yield a sufficiently large SPD/SPC cross-section to physically accommodate the desired number of CMs and Amps. Some of the microwave modes that can be chosen for SPCA high-power operation include transverse electric TE and transverse magnetic TM modes inside cylindrical, rectangular, and square cavities and waveguides.

In cylindrical cavities one could use TE_{ml}° or TM_{ml}° modes, where m and l denote the azimuthal and radial periodicity of the wave, respectively [1]. In rectangular and square structures, $TE_{pq}^{\square}$ or $TM_{pq}^{\square}$ modes can be used (p and q in this case denote the wave periodicity in the x and y direction). Here, $\circ$ denotes cylindrical structures and $\square$ denotes rectangular/square structures. Lower-order modes with small cross-sections such as $TE_{10}^{\square}$ modes are not considered here. In this embodiment of the SPCA, TE_{ml}/TM_{ml} modes with $m \geq 1$ and $l \geq 1$ are preferred due to the fact that they require larger cross-section structures than the $TE_{10}^{\square}$ mode, which allows for the insertion of a larger number of CMs/Amps (i.e., $n \gg 1$).

V. Signal Polarization

Depending on the coupling mechanism CM$_1$ used for feeding the input signal into the SPD, the SPCA should allow the injection of signals that are linearly polarized and/or circularly polarized (elliptical polarization is also possible).

If asymmetric modes (TE_{ml}/TM_{ml} with $m \neq 0$ for cylindrical structures and $m, l > 1$ for rectangular structures) are used in cylindrical and square cavity/waveguide structures, then the SPCA should be able to amplify circularly polarized signals. That is to say, under these conditions, the SPCA should accept a circularly polarized signal at its input and should output an amplified signal with the same circular polarization.

If a symmetric mode is used ($m = 0$ in cylindrical and $m = l > 1$ in rectangular cavity/waveguides), only linearly polarized signals can be boosted and consequently the SPCA will output linearly polarized amplified signals.

VI. S-band SPCA Prototype — Transverse Magnetic TM_{110}° Mode

The objective of this point design is to demonstrate that the proposed SPCA mechanism can provide an immediate and viable option for achieving stable and reliable high-power microwave amplification in a compact structure. As stated earlier, the SPCA is based on the principle of spatial (air) power combining and thus should avoid thermal issues typical of solid-state power combining methods. A key advantage of this game-changing concept is that, when compared to conventional tube amplifier counterparts, it offers a factor of 4 reduction in size. Another advantage of the SPCA is that it uses an array of mature solid-state MMIC amplifiers, thus providing graceful degradation.

We have implemented a basic narrowband version of the SPCA that consists of an input cylindrical cavity (SPD), an output cylindrical cavity (SPC), four sets of electric probes (CMs), and four MMIC amplifiers (Amps). (For this design, $n = 4$.) The cavities operate in the transverse magnetic TM_{110}° mode[4] [1], which has an azimuthal and radial periodicity equal to 1, i.e., $m = l = 1$. In this case, the frequency of operation of the microwave signal is 2.4 GHz (S-band). Figure 2 shows a schematic of the S-band SPCA. A signal generator produces the input signal, which is injected into the input cavity via two magnetic loop antenna probes that are placed orthogonal to each other around the cavity edge wall. A phase shift of 90 deg is provided between the two loop antennas via a 90-deg hybrid to produce a rotating (circularly polarized) TM_{110}° mode [2] inside the SPD cavity. It should be noted that if only one loop antenna is used, this would result in the generation of a linearly polarized TM_{110}° mode inside the input cavity.

Four electric probes are used to extract power from the input cavity for subsequent amplification by the MMIC amplifiers. The amplifiers are commercial-off-the-shelf Mini-Circuits devices model ZHL-30W-252-S+ that require 28 V at 5 A to operate. The Amps have a gain of 47 dB and can produce a maximum output power of 30 W.

After being amplified by the Amps, the signals are injected into the SPC output cavity via four electric probes, which are critically coupled (with coupling factors near unity), where the TM_{110}° mode coherently combines these signals to produce a high-power version of the mode within the SPD.

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[4] J. E. Velazco, "The Study of Synchronous Beam-Wave Interactions for the Generation of Coherent Microwave Radiation," PhD Dissertation, George Mason University, 1994.
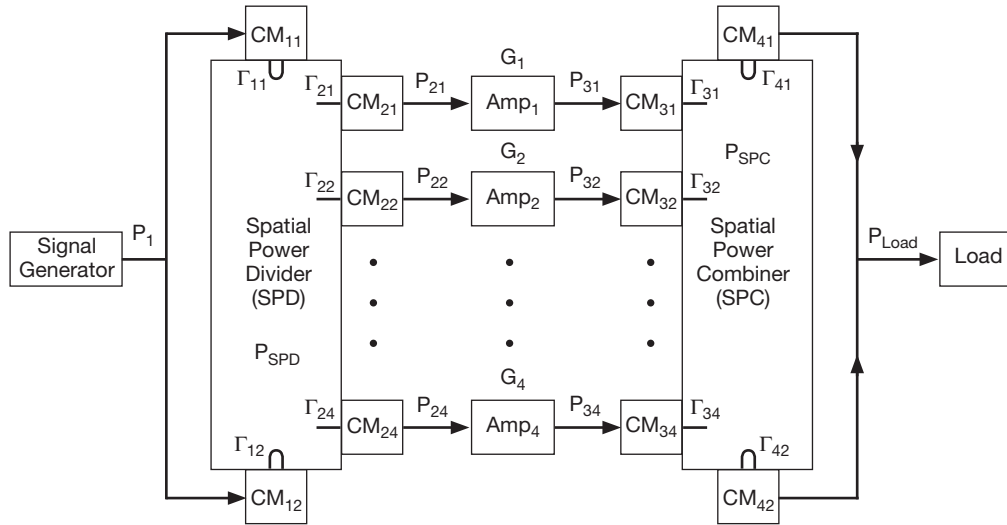
Figure 2. Schematic of the S-band SPCA amplifier.

High power is extracted from the SPC output cavity via two magnetic loops (CM_{41} and CM_{42}) whose output is combined via a 90-deg hybrid prior to being delivered to the load. Figure 3 shows the S-band SPCA experimental setup.
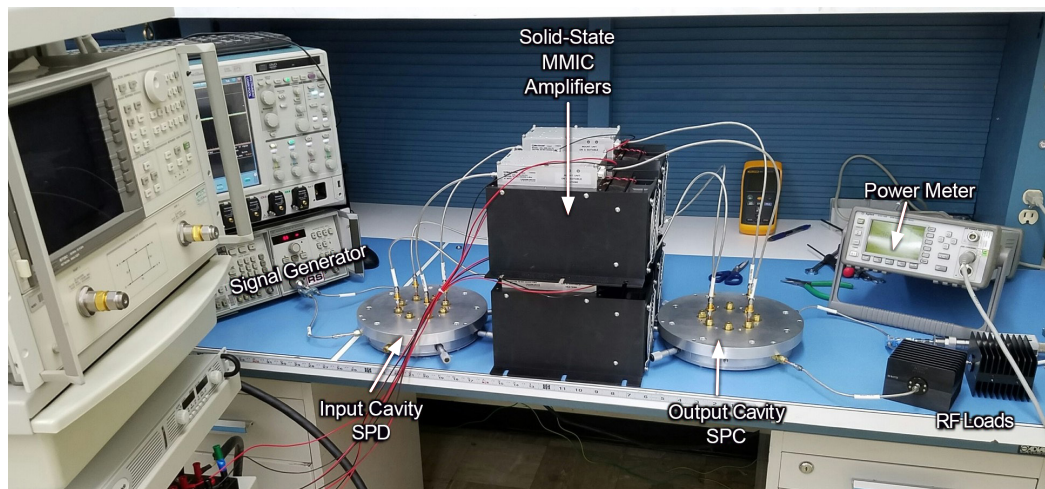

Figure 3. Picture of the entire S-band SPCA experimental apparatus.

A plot of measured output power as a function of input power is shown in Figure 4 for a frequency of 2.4 GHz. Note that with an input power of 5 mW, an output power of 100 W is obtained. This results in an SPCA gain of 43 dB. The efficiency of the SPCA is dictated mostly by the conversion efficiency of the MMIC amplifier, which in this case is ~40 percent.
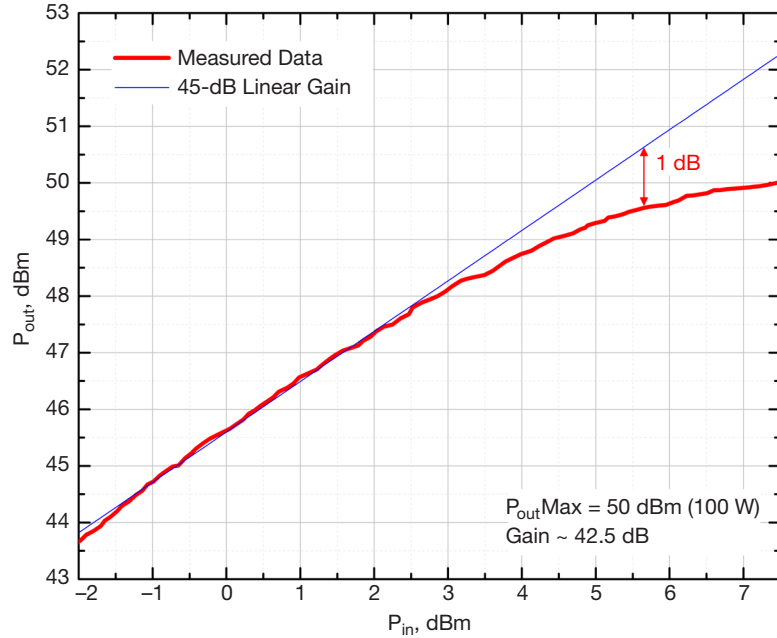
Figure 4. Measured SPCA output power as a function of input power. Note that 100 W (50 dBm) is obtained with an input power of 7 dBm. The operating frequency is 2.4 GHz.

These preliminary results demonstrate the novel spatial power combining of the SPCA. The SPCA concept represents a big step in the development of compact, reliable high-power microwave sources that offer graceful degradation and feature the high reliability of solid-state MMIC amplifiers.

Future plans for this current S-band SPCA design are to increase the number of MMICs to a total of 16, i.e., $n = 16$. With 16 MMICs, the expected output power is 400 W with an associated gain of 50 dB and 50 percent efficiency.

More advanced high-power S-band designs include 2-kW SPCAs using 80 MMIC amplifiers and a 10-kW SPCA using 400 MMICs. In addition, as mentioned before, several SPCAs could be arranged in tandem to increase the overall gain. For instance, if a two-cavity SPCA using one set of MMICs produces 30 dB of gain, using three cavities (with two sets of MMICs) can yield 60 dB gain.

In addition, the SPCA should be easily scaled up to work at higher frequencies, including but not limited to, X-, Ka-, and W-band frequencies. Figure 5 shows an image of an X-band SPCA designed to deliver more than 1 kW of microwave power. In this X-band SPCA, 18 60-W MMIC amplifiers are coherently spatially power combined to produce 1 kW of power. In Table 1, we list SPCA designs for X-, Ka-, and W-band that we plan to pursue in the near future.
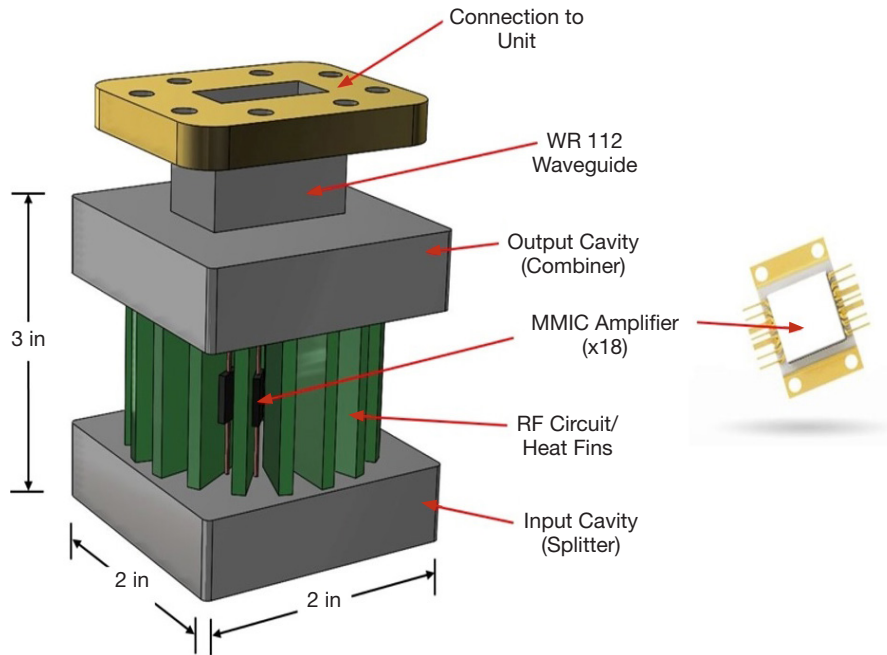
Figure 5. X-band SPCA design capable of producing 1 kW of power by power combining 18 solid-state MMIC amplifiers.

Table 1. SPCA future designs.

Parameter	X-Band (8.4 GHz)	Ka-Band (32 GHz)	W-Band (94 GHz)
Cross-Section	$2'' \times 2''$	$0.5'' \times 0.5''$	$0.2'' \times 0.2''$
Height	$3''$	$1''$	$0.4''$
Number of MMICs	18	8	6
SPCA Output Power	1080 W	65 W	5 W

VII. Key SPCA Advantages

Microwave power combining is commonly used in commercial power amplifiers where MMICs are arrayed on microstrip boards to produce high-power radiation. Power combining is achieved via power combiners that are imbedded on the microstrip boards. These solid-state power combiners tend to become single points of failure. Due to the high power densities generated by the high-power signals, thermal hotspots occur on this solid-state power combiner which tends to fail, rendering the whole amplifier useless.

A key advantage of the SPCA is that the only active elements used in this mechanism are reliable solid-state MMICs. The usage of several MMICs allows the generation of high power and enables a key SPCA feature: graceful degradation. In the event of failure of several MMIC Amps, it is expected that the SPCA will continue providing high-power radiation.

Another key advantage of this concept is that, when compared to conventional tube amplifiers, it offers a factor of 4 reduction in volume and reduced DC power. Unlike tube counterparts that require high operating voltages (with associated large power supplies), the SPCA requires low voltages (small power supply). The ability to have large output power in a small, compact package, with the added advantage of thermal stability due to spatial (air) power combining is likely to lead to revolutionary new instruments for future cloud radar in Earth science, and planetary, comet, or asteroid radar sensing.

In general, the SPCA can revolutionize the microwave market industry by offering a high-power, reliable microwave source in a very small package that has numerous applications in phase array radar, communications, food processing, and microwave materials processing. All these applications cut through several arenas including science, the military, and industry.

VIII. Future NASA Applications

The SPCA, once fully developed, can become the amplifier of choice for NASA's ground and flight missions. Compact S-, X-, and Ka-band SPCAs could be used for ground DSN communications. X-band arrays could also replace klystrons in the Goldstone Solar System Radar. Moreover, Ka-band SPCAs could become the device of choice for future flight missions for both high-bandwidth communications and radar.

In general, any future NASA mission can be furnished with SPCAs for both radar and communications transmitters. In addition, the field of wireless power beaming could explode with the proper implementation of SPCAs. Power beaming could be used to power smaller spacecraft from larger ones. Planetary rovers furnished with SPCAs could power beam smaller rovers for exploration of planetary landscapes.

IX. Conclusions

We have presented a new concept for high-power microwave generation. The spatial power combining amplifier[5] uses a new mechanism for coherently combining the output of COTS amplifiers such as solid-state MMIC amplifiers. We constructed and successfully tested an S-band SPCA prototype that was able to deliver 120 W of power with a gain of 50 dB and 50 percent efficiency.

The primary objective is to replace conventional vacuum-tube amplifiers such as klystrons, commonly used in DSN ground stations, with SPCAs that are capable of equivalent performance while offering a factor of >4 reduction in size. In addition, we strongly believe that SPCAs will be well-suited for the next generation of radar and communications systems for future flight missions.

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[5] J. E. Velazco, "Spatial Power Combining Mechanism for the Generation and Amplification of Electromagnetic Radiation," JPL NTR 50016, Provisional Patent CIT File No.: CIT-7505-P.

References

[1] J. E. Velazco and P. H. Ceperley, "A Discussion of Rotating Wave Fields in Microwave Applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 2, pp. 330–335, February 1993.

[2] P. H. Ceperley and J. E. Velazco, "Tuning a Rotating Mode Resonator," *Review of Scientific Instruments*, vol. 66, no. 1, pp. 256–260, January 1995.