Spatial Power Combiner Technology

Davide Passi[1], **Alberto Leggieri**[1], **Franco Di Paolo**[1], **Antonio Tafuto**[2], **and Marco Bartocci**[2]

[1]University of Roma "Tor Vergata", Via del Politecnico 1, Roma 00133, Italy
[2]Elettronica SpA, Via Tiburtina Valeria Km 13.7, Roma 00100, Italy

Abstract— This article describes the spatial power combining techniques dealing with the state of the art of Spatial Power Combiners (SPC) considering recent developments. A brand-new splitting scheme is proposed where different types of SPC are grouped according to the space where power combining and splitting occur. This paper should provide compendium knowledge for SPC design and selection of the opportune SPC basing on the target application.

1. INTRODUCTION

In airborne and space applications, characteristics like reliability, size, efficiency and weight of the Power Amplifiers (PA) assume a very important role in the selection of the proper PA to be employed. High RF power levels are demanded to vacuum tubes amplifiers like TWTA, Klystron or Gyrotrons but those have the main disadvantage to use heated wires and bulky magnets or electromagnets that give greater size and weight and reduce efficiency [1]. So, combined Solid State PA (SSPA) would be greatly appreciated if they could give at least the same order of magnitude in RF power levels, since in this case graceful degradation is increased. Spatial power combining technique is an alternative one to combine many SSPA reducing to a minimum extent the combining losses [2–4].

This article deals with the state of the art of Spatial Power Combiners (SPC) and their characteristics [14]. In addition, it is proposed a new splitting scheme for the SPC family, grouped respect to the ambient where combining and splitting take place, as shown in Figure 1. The fundamental SPC Amplifier's concept is to provide a large power value with minimum losses. In SPC the electromagnetic energy coming from input is divided as much as possible in the space, without using transmission lines, and it is sent to many SSPA's. After amplified energy is collected, it is sent to output port with the lowest possible number of transmission lines.

SPC employees probes, antennas or transitions to take the spatial RF energy and send it to a two wires transmission line: the use of connectors at the amplifiers ports exclude the combiner to belong to the class of SPC. The system's quality is usually determined from its efficiency. SPC efficiency can be defined as how much power is sent to amplifiers respect to how much power is provided to input port, such as it quantifies the capability of the combiner to intercept incoming energy P_I and distribute it to N energy dividing/combining internal ports, that is

$$\eta = \frac{\sum_{k=1}^{k=N} P_{O,k}}{P_I}$$

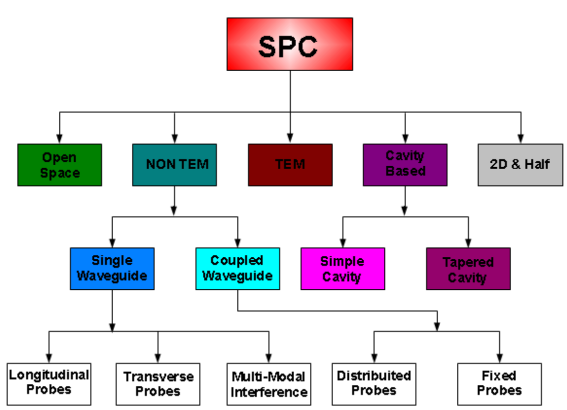

Figure 1: SPC's family.

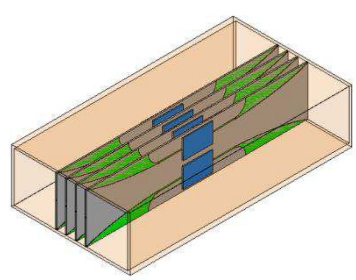

Figure 2: Single waveguide SPC with fin lines.

where $P_{O,k}$ is the input power at the k-th amplifier. Referring to scheme in Figure 1, the distinction between different types of SPC is done considering the propagation modes in the medium. Thus, there are TEM and Non TEM spatial combiners, cavity based, open space and 2D&Half ones.

2. NON TEM SPATIAL POWER COMBINERS

Non TEM SPC use waveguides to confine RF electromagnetic energy and it is composed by three families: the single waveguide family, with longitudinal probes and transverse probes, the coupled waveguides and the multimodal interference families.

RF probes can be directly realized on amplifier, usually a MMIC, or out of them. RF probes can be realized in many ways, as monopoles, dipoles, patches or slots or combinations among them. In many other cases Fin Line transition are realized, especially when wide band applications are needed.

2.1. Single Waveguide

The Single Waveguide SPC (SW-SPC) is the most common amplifiers among all Non TEM SPC. Single waveguides with longitudinal probes (SW-LP-SPC), uses transitions placed along the direction of energy propagation to couple energy with amplifying devices: the most used transitions are the Fin Lines [5]. The general assembly of these kind of SPC's is shown in Figure 2. There are several Fin Lines tapers such as linear, exponential and sine-square taper (and many others one) and they can be printed on single or double face of a substrate, called card. Furthermore to meet the power requirements many stacked cards can be employed into a single waveguide. The cards more distant by the waveguide's center are less excited than closest ones. This effect is due to the electric field distribution. An Electromagnetic Band Gap (EBG) [6] can be inserted in the waveguide to improve the probes feeding. In this way electric field distribution (TE_{10}) is made different from half sine shape and the uniform probes exciting and the system balance is increased allowing to utilize more cards. Due to the use of EBG, the operative band is considerably decreased.

Fin Lines are also distinguished by transition's type, usually to micro-strip; thus, a slot line to micro-strip transition and an antipodal one exist, where the electric field rotates from its initial polarization to the orthogonal one. After quasi-TEM mode is allowed inside a two wire transmission line, usually a microstrip, waveguide can be made wider to stack more amplifiers: This result in a sort of oversized waveguide is used. Now, we show an example taken by our experience: a Ka band SPC [3]. This SPC contains a Quad Fin transition type, but only two cards are inserted inside the WR28 waveguide, due to small size of this waveguide; so this combiner would hold only 8 MMIC's. To overcome this limit, we used Tee-Junctions at input and output so that our SPC can now combine 16 MMICs. A sketch of the combiner and its performance are shown in the Figures 3 and 4 below.

Single waveguide with Transverse Probes (SW-TP-SPC), uses these last placed orthogonally to the direction of energy propagation to catch and send the amplified energy.

The whole set of the amplifiers elements and probes are named Grid Amplifier [7]. The basic concept in SPC Grid Amplifiers is to intercept the incoming signal with a defined polarization, amplify it with the active device and then send the amplified signal using the orthogonal polarization respect the incoming one. In Transmission Type Grid Amplifiers (TT-GA) two polarizers are adopted to allow the electric field to pass through with a specified polarization and they are useful to decouple somehow input and output waveguide ports reflections, thus increasing the stability of

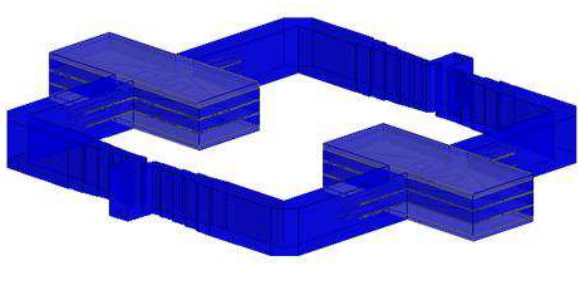

Figure 3: Ka band SPC: sketch of the microwave side.

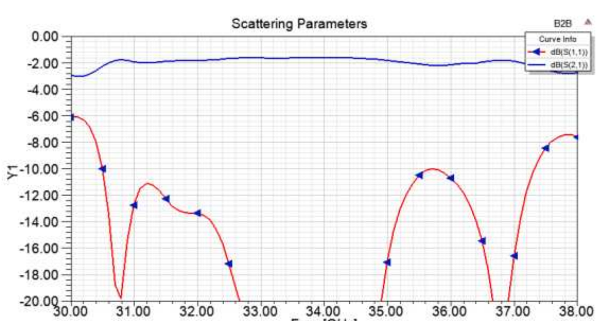

Figure 4: Ka band SPC performance.

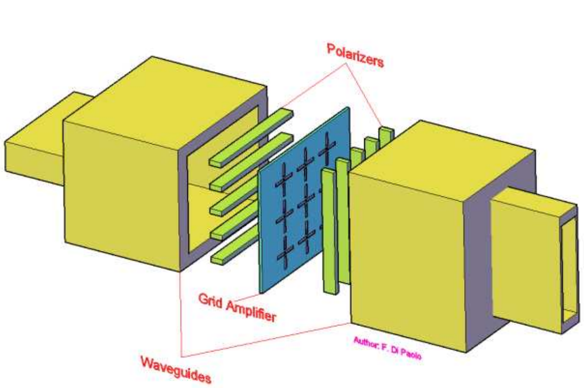

Figure 5: Transmission type grid amplifier.

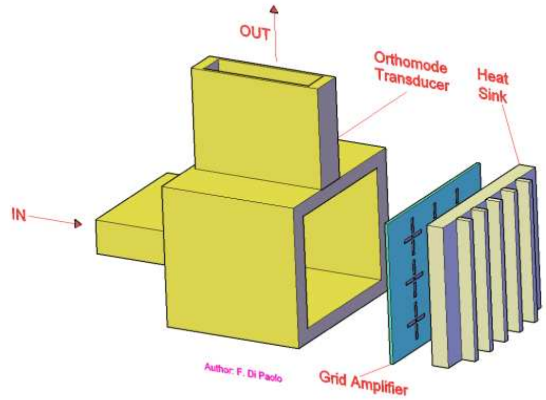

Figure 6: Reflection type grid amplifier.

the amplifier from oscillations. In Reflection Type Grid Amplifiers (RT-GA) the same MMIC is employed in reception and transmission so a short circuit can be placed back of it. MMIC amplifies and rotates the electric field while an ortho-mode transducer, or a couple cross polarized horn antennas, discriminates the polarizations. Examples of TT-GA and RT-GA are given in Figures 5 and 6. The reflection type has more heat removal capacities than the transmission type because the second one spreads the heat through the metal of the waveguide while the first one has heat sink placed just back the MMIC.

2.2. Multimodal Interference Combiners

A different type of SPC is the Multimodal Interference SPC (MMI-SPC), uses the interferences among many propagating modes in an overmoded waveguide. The resulting effect is the same found in optics, and first discovered by the English physicist William Henry Fox Talbot through experiments in optics. He discovered that in an overmoded waveguide the exciting field at incoming port replicates N times at given distance depending by operating frequency and waveguide dimensions. A picture of this phenomenon in reported in Figure 7.

This multimodal interference effect is also named "Talbot's effect" and it is selective in frequency due to its nature. The field of SPC's based on Talbot's effect is actually under analysis [8], and the effective utility as an amplifiers has to be still proved with some experiment.

2.3. Coupled Waveguides

The Coupled Waveguides SPC (CW-SPC) use two waveguides connected between them through two wires transmission lines [9]. These SPC use amplifying devices that are outside the probing and combining area, that is they fail the implicit concept of all SPC, but they are anyway "spatial" when probing and combining energy.

Two examples of Distributed Probes Coupled Waveguide SPA are shown in Figures 8 and 9.

A common characteristic of all coupled waveguide SPC is that they use short circuits at one extreme of the waveguides, so a stationary wave regime is generated. Two kinds of electromagnetic coupling between the waveguides and the two transmission lines are used, which can be defined as E-coupling, using E-probe, and H-coupling, using H-probe. This kind of amplifiers reduce a lot the

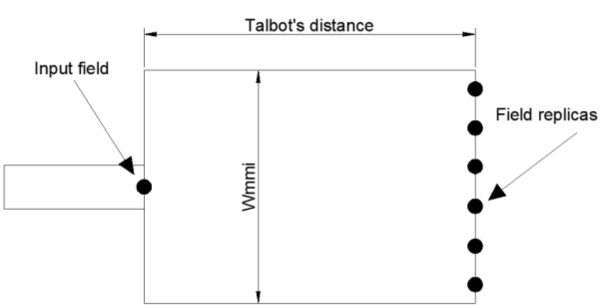

Figure 7: The concept of MMI in overmoded waveguide.

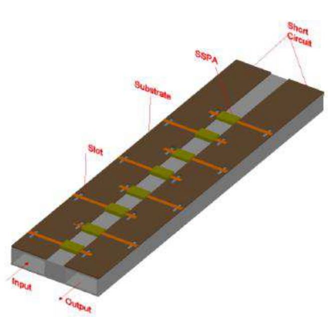

Figure 8: Distributed probes H-coupled waveguide SPA (DPHCW-SPA).

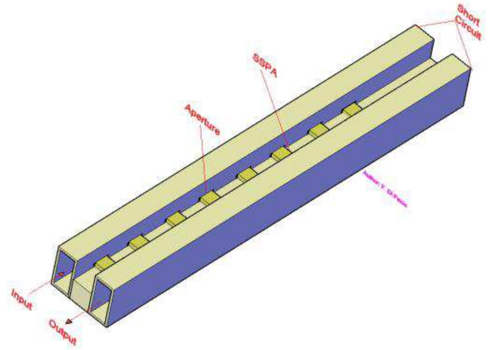

Figure 9: Distributed probes E-coupled waveguide SPA (DPECW-SPA).

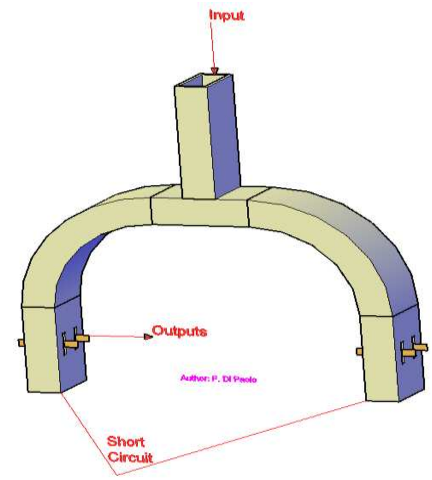

Figure 10: Fixed probes E-coupled waveguide SPC, with 8 E-probes.

risk of unwanted oscillations due to input-output coupling. Coupled Waveguides SPC are divided in two subgroups, the distributed probes group and fixed probes group. In the first case, probes are located along the waveguide, while in the second case probes are located just near the shorting wall of the waveguide.

The operating bandwidth of this kind of SPC using distributed probes is usually around 10–15%, evidently much smaller than the operating bandwidth of the used waveguide. This is due to the fact that in addition to use short circuits at one extreme of the coupled waveguides, that creates a regime of stationary waves inside the waveguides where positions of maxima and minima are highly frequency dependent, the multiple reflections at the distributed probes interacts between them causing an additional bandwidth reduction. Often, sliding shorts are used instead of fixed position shorts, to allow some kind of tuning so that maximum energy transfer is reachable, and consequently a maximum efficiency for this kind of amplifier is obtainable.

Fixed Probes Coupled Waveguides SPC (FPCW-SPC) has probes placed inside waveguide in a way that there is not a distributed coupling. An example is shown in the Figure 10, for the case of E-coupling. The operating bandwidth of Fixed Probes Coupled Waveguide SPC (FPCW-SPC) is wider than Distributed ones. This is due to the fact that the monopoles used to capture the energy inside the waveguide can be tuned to proper matching the frequency dependent reflections at the waveguide short circuit and it is possible to cover the full TE_{10} mode operating bandwidth.

H-coupling probes, that are slots, are realized at the waveguide widest side, and microstrips are used to connect the slots between the two waveguides. Slots are placed near the waveguide narrowest side, at the top, where the electric field is at its minimum value, and the magnetic field is used to couple energy to the top microstrip. The incoming energy, at the input waveguide, is captured by microstrips probes placed on these slots and sent to other slots realized on the output waveguide. To make an amplifier, SSPA's are placed between the microstrips.

The E-coupled mechanism between the waveguide and microstrip is realized making an aperture at the center of the waveguide widest side, and letting a microstrip to enter inside the aperture to capture energy inside the waveguide. Since such apertures are made at the center of the waveguide, here the electric field is at its maximum value and just this field is used to couple energy to the microstrip. The incoming energy at the input waveguide is captured by such microstrips E-probes placed inside the apertures and sent to other apertures realized on the output waveguide. To make an amplifier, SSPA's are placed between the microstrips. E-probes inside the waveguide are less radiative than H-probes so they present a good combining efficiency, in addiction E-probes have a 5% useful bandwidth wider than H-ones thanks their non resonant aperture.

3. TEM SPATIAL POWER COMBINERS

TEM SPC use TEM transmission lines to confine RF electromagnetic energy [10]. The simplest and well known TEM structure is the coaxial transmission line. In this section are going to illustrate two versions, the classic circular and the square one. Another peculiarity of this kind of SPC is to present an ultra-wide operating band, this is due to the fact that TEM transmission line allows the

RF to propagate from DC to the first high order mode cutoff frequency (depends on its geometric size). A linear relationship exists between frequency and wavelength so no dispersion arises and pulsed signal can pass without distortion. To full cover the operating bandwidth a Fin Line is employed to capture the incoming TEM. EM power density has a dependence along the radius r as $1/r^2$ and Fin lines have to be designed to compensate this effect, thus Fin Line nearest the external radius need to have a wider aperture of the Fin Line nearest the inner one. Metallic carrier of the circular coaxial SPC, where Fin Lines will be placed on, have a wedge profile to form all together the cylindrical transmission line. This fact comply the making process because each carrier have to perfectly overlap with closed ones. In addiction an ad-hoc heat sink is applied due to its no standard shape.

To solve this problem a square coaxial (Squarax) SPC can be employed [2].

Due to its symmetric nature it has not mechanical problem and its performances are similar to the circular coaxial SPC.

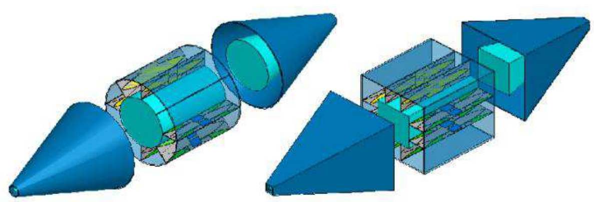

Figure 11: Circular and square coaxial TEM SPC's.

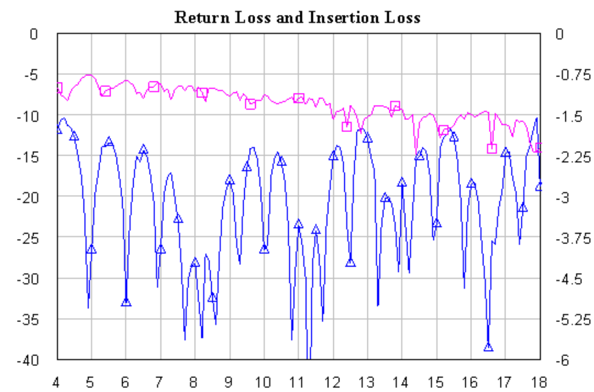

Figure 12: SQUARAX coaxial SPC performance.

In the whole cases a coaxial taper is employed to join the wider and the standard sized coaxial transmission line together. The performance of the Squarax SPC is reported in the Figure 12. As mentioned before, TEM SPC's are the best choice when wide operating bandwidth is required, greater than what can be reached for a waveguide.

4. CAVITY BASED, OPEN SPACE AND 2D&HALF SPATIAL POWER COMBINERS

Cavity Based SPC (CB-SPC) use a closed cavity excited by an input port, and the output ports are realized inserting probes inside such cavity [11]. Two different groups exist in this family and differ from how the input port couples with the cavity: if the coupling is made through a conical transmission line the SPC is named in literature as Conical Transmission Line SPC or Tapered Cavity SPC, otherwise it is named in many ways like Radial SPC, Coaxial SPC or Simple Cavity SPC. In CB-SPC's even if no probes, transitions and active devices are used the structure cannot work an ordinary transmission line, since such CB-SPC's use cavities to realize the SPC function. Two different ways exist to couple the ports to the cavity: It is possible to couple the cavity magnetically or electrically. Magnetic coupling are usually preferred in high power SPC's, to decrease somewhat the problem of electric field discharge when using electric coupling. This combiner family has not been accepted in the great family of SPC due to the external place of the amplifying devices that are joined with cavities through connectors. Tapered Cavity SPC, usually, has a central coaxial connector and many peripheral ones where the external PA's are connected. The central connector excites the cavity after a proper impedance matching realized through a conical transmission line. Different from previous SPC Cavity based, Simple Cavity SPC doesn't use tapering at the central connector. Their efficiency is very high due to the fact that they use closed cavities and thus energy is well confined inside it.

Open Space SPC (OSS) use amplifiers connected to probes placed in an open space environment [12]. The type of the used probes are dependent to the frequency and operating bandwidth of the system, but in general dipoles or wideband tapered antennas are the most employed ones, respectively for narrowband and wideband applications. In addition, input probes are placed in orthogonally polarization to the output ones to avoid the raise of unwanted oscillations due to coupling between input and output. The probes used in single waveguide SPC are also employed in the open space family. Usually lenses are used to focus the beam to and from grid amplifier. The lens is a Gaussian beam former and gives an excellent phase and amplitude distribution due to the necessity to an uniform feed of the grid amplifier. Two horn antennas can be employed to increase the field uniformity and to avoid to use bulky lens. This is shown in the Figure 14.

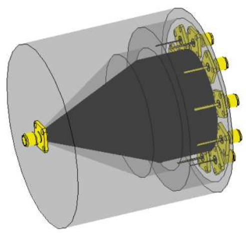

Figure 13: Tapered cavity SPC.

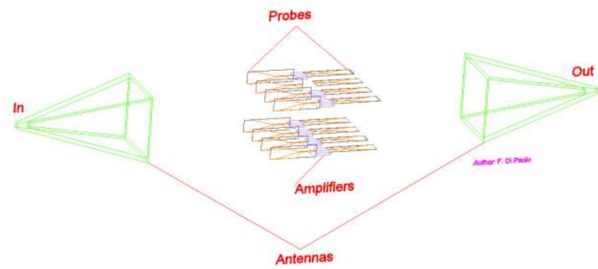

Figure 14: Open space spatial power amplifiers with horn antennas.

2D&Half SPC, that are two dimensions and half SPC, are named in that way due its little vertical dimension respect the other [13]. Probing and summing energy is made the TE surface wave. This family remembers SIW technology (Substrate Integrated Waveguide) or micro open space SPC. In general, with 2D&Half SPC's it is quite difficult to have good heat management for the active devices, and eventual application to high power SPC must be well investigated. This is because heat sink can disturb the surface wave propagation.

5. COMMON TECHNOLOGICAL AND OPERATIVE ASPECTS IN SPC DESIGN

SPC, grouped in any ways, as shown in Figure 1, share some problems related to the employment of different technologies in the same device and the use of electromagnetic bounded space. Common technological and operative aspects are discussed in this section.

A considerable problem regards the High Order Modes (HOM) excitation. Unless such excitation is desired, as in MMI-SPC's or SPC in oversized waveguides, in all the other cases it is an unwanted situation. SW-LP-SPC's should be carefully loaded by Fin Lines to reduce the risk of HOM. SW-TP-SPC's are less prone to excite HOM, at least when they are used as TT-GA; in RT-GA, the design should be oriented with attention to avoid HOM excitation. Coax-SPC's use wider dimension of what strictly necessary, to allow the use of as many amplifiers as possible between the inner and outer coaxial conductor, and this oversizing is cause of possible HOM excitation.

Another problem regards the uncollected power. It is the power that it is not captured by the probes, but travels through the transmission line or/and is reflected back at the origin. This uncollected power is cause of decrease in efficiency, since it is not used by probes and consequently it is not combined at the output. Uncollected power is present in almost all SPC's we have reported in this document, with an exception: the CB-SPC's. These last SPC's use in fact cavities for power dividing and combining process, and in a good design all of the cavity energy participates to this process. It is for this reason that CB-SPC's have the highest combining efficiency.

The available area for active devices represents a notable topic: Whenever a transmission line based SPC is used, when the frequency increases there is a reduced available space for MMIC's. This is true for non-TEM SPC and particularly for TEM-SPC. For a Coax-SPC it is not so simple to enlarge the area to place MMIC's, since in this case it is also necessary to realize the necessary place inside the coaxial internal conductor. In general, any type of SPC which employ oversized waveguide resolve in some way the problem of limited space for MMIC's.

Power Supply Routing (PSR) is an important aspect of SPC design: It is strongly dependent to the technology used to realize the SPC. In general the PSR complexity increases with the number of active elements inside in the SPC Amplifier, but it is less critical when amplifiers are placed outside the SPC.

In design of SPC, particular attention needs to be given to the thermal management: SPC's using Fin Lines, regardless if they are purely passive or active, have a peculiar thermal problem: The possible bending of the Fin Line vs. temperature. If a bending occurs, the Fin Lines does not intercept the maximum possible field, but only a port of it. Substrate bending vs. temperature can be reduced a lot if hard substrates are used, as Alumina or Aluminum Nitride. The drawback to use hard substrates for Fin Lines is that they load dielectrically the air inside the transmission line. First of all, brazing the MMIC PA's is necessary, rather than die attach with epoxy. For high power SPC's is the heat removal capacity that limits the reachable power from such amplifiers, and a compromise between output power, available space for the SPC and thermal removal capacity must be found.

Mechanical considerations during the design are mandatory when several technologies are combined, as happens with SPC approach. SPC's using probes with soft substrates should be carefully mechanically designed to respects the system, requirements to vibration survivability. The tolerance to vibration is dependent to the mechanical methods used to assembly the SPC. Sealing is another issue. We have seen that the most used SPC Amplifiers employ cards to compose the structure. In such cases, it is difficult to have a hermetic SPC so it is better to use hermetic packages for the PA's.

6. CONCLUSIONS

In this work we have described the spatial power combining techniques, dealing with the state of the art of the spatial power combiners. An innovative SPC family tree has been introduced, based on propagation media and type of probes, longitudinal or transversal. All the branches of this tree have been analyzed and a comparison among them has been discussed. Finally, common problems in every SPC have been analyzed: these are HOM excitation, Uncollected Power, available area for active devices, power supply routing, thermal management and mechanical considerations.

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