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Spatial power combining techniques for semiconductor power amplifiers

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1. Introduction

Growing demand on special signal modulation schemes in novel radars and ability to transmit relatively long pulses cause the Travelling Wave Tubes (TWT) to be constantly replaced by new concepts of power amplifiers. Solid-state power amplifiers appear to be a good candidate, however, the output power from a single transistor module is still relatively low. The only available solution is that of combining output power from a number of semiconductor amplifiers. To accomplish this, one can use, classical and well-known, two-way power combiners (like Willkinson type) or specially-designed new type of multi-input combiners. Current requirements for radar working modes imply using active antenna arrays, thereby providing multifunction ability. The active antenna concept assumes the use of transmit-receive modules (T/R), each comprising a power transistor. The overall transmitted power is then a function of the sum of the output powers from each T/R module, and the power summing operation is performed in free space.

On the other hand, in some radar applications (or generally, where a power amplifier is needed, be it electronic warfare or jamming), the central power transmitter is still desired. The older applications are based on TWTs, and although they give enough power, they carry a number of disadvantages. The main are as follows:

- TWTs generally offer low duty factor (although some of them are approaching up to 100%),
- they need special power supplies, which are dangerous due to tube working voltages in the range of kVolts
- reliability is limited due to erosion of inner electrodes inside the TWT
- reliability system is two-state, a tube works or does not; any failure results in a complete malfunction of the radar.

Additionally, in higher bands there are no solid-state power sources with enough power.

The conclusion and current trends are that there is a constant need for combining power from a number of sources.

2. General combining techniques

2.1 Types
2.1.1. Multilevel combining
Combining a number of sources with the use of basic two-input power combiners implies the necessity of using a number of them. As a result, the overall power combiner is formed as a tree-like structure. The number N of power sources (transistors) has to be a power of 2. For N amplifiers, the resulting combiner structure contains $p = \log_2 N$ levels (Fig. 1).
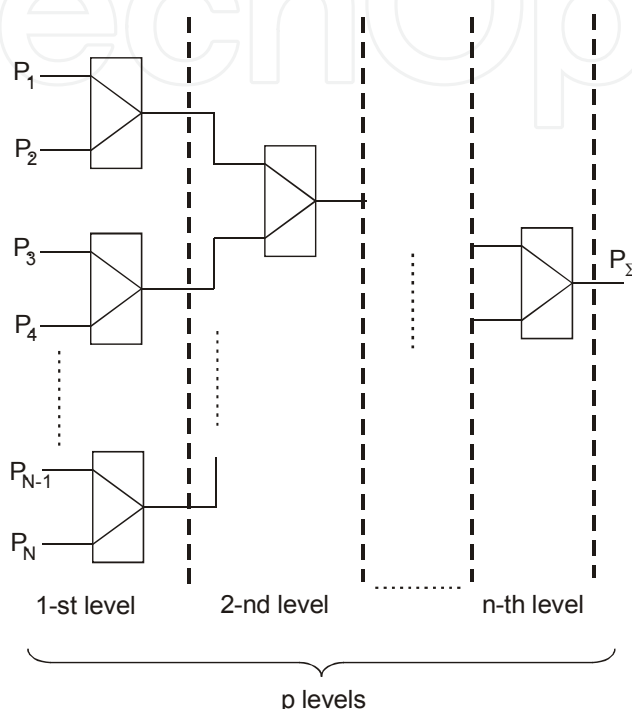

Fig. 1. Combining structure based on two-input power combiners

For a cascaded network combining N input signals the number of N-1 basic two-input combiners has to be used. The multilevel combining scheme is easy to implement. The two-input power combiners are well-known and their design is well-developed. Depending on the chosen power transmitter structure, the multilevel structure may be fabricated on one big PCB, forming a packet-like power module, or each of the two-input combiners may be assembled and packed separately. Due to the fact that they form p levels, insertion losses of the final structure are p times insertion losses of the basic structure. Therefore for each of the input power path there is insertion loss p times higher than that of one basic two-input structure. Another serious drawback of cascaded devices is possible accumulation of phase mismatches introduced by each of the basic structures.

2.1.2. Spatial combining
The term "spatial combining" means combining a number of input power sources with the use of simultaneous addition of input signals in a kind of special structure with multi-couplings or multi-excitations. Input signal sources are distributed in space and excite their own signal waves inside a specially designed space intended for power addition. The

structure of spatial power combiner may have a number of input ports and one output port, whereas the combining takes place inside the structure.

To complete a power amplifier system two of such structures are needed. The first one acts as power splitter, connected to a number of amplifying submodules, and the second collects output power from these submodules.

The second available solution is when the combiner has got only one input and one output port. The amplifying modules, or simply transistors, are incorporated inside the combining structure, most frequently a hollow metal waveguide-like structure, which contains a set of specially designed probes/antennas inside, each one connected to a power transistor, and the same set at the transistor outputs. The input set of probes reads EM field distribution, it is then amplified, and finally the output set recovers field distribution with amplified magnitude. This structure may be regarded as a section of an active waveguide.

2.2 Theory

For the basic two-input structure the relationship between input power and output power is given by:

$$P_{\Sigma}\big|_2 = T^2\left(\sqrt{P_1} + \sqrt{P_2}\right)^2 \tag{1}$$

where the combiner is characterised by the scattering matrix [S] (Srivastava & Gupta, 2006):

$$[S] = \begin{bmatrix} R & T & T \\ T & R & I \\ T & I & R \end{bmatrix} \tag{2}$$

For purposes of simplification, isolation (I) is assumed to be equal to 0 and the combiner is perfectly matched at all its ports (reflection R=0).

In order to design a power combining network one needs to be familiar with the influence of the combining structure on final output power. This has to cover the influence of individual characteristics of combining sub-structures and the number of levels, as well as, the output power degradation as a function of failed input amplifiers. Such knowledge allows to calculate and predict a drop of radar cover range in case the amplifying modules fail.

For higher value of N (and number of levels p), when the equivalent insertion losses become higher, a specialised spatial combiner is worth considering. In reality, it may turn out that insertion losses of a specially designed multi-input combiner (with, for example, eight-input port) may be comparable to those of a two-input structure. That means that usually it exhibits lower insertion losses than the equivalent cascaded network.

Assuming approach shown in Fig. 2 the combined output power is associated with the normalized wave b_n in case the input ports from 1 to n-1 are excited by input powers P_1 to P_N (i.e. $N = n$-1).
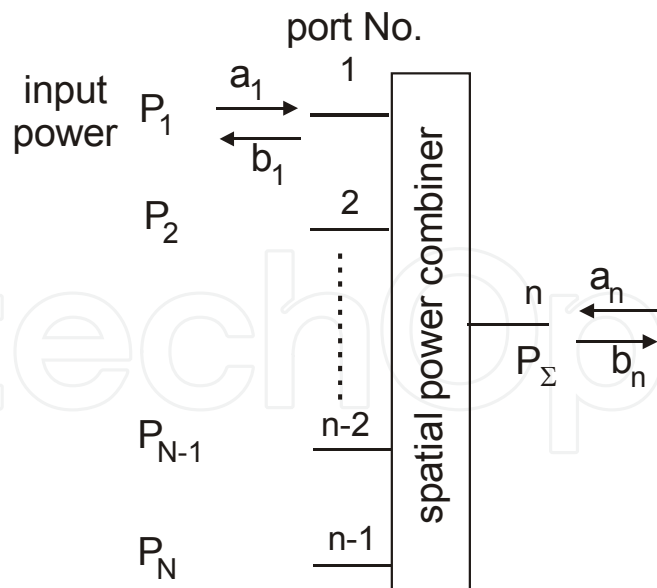
Fig. 2. General spatial power combiner – excitation of the ports

$$
\begin{bmatrix} b_1 \\ \vdots \\ b_{n-1} \\ b_n \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & \cdots & S_{1n} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ S_{n1} & \cdots & \cdots & S_{nn} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ \vdots \\ a_{n-1} \\ 0 \end{bmatrix}
\tag{3}
$$

In ideal case (neglecting the insertion losses, and assuming ideal matching and isolations) the general formula for power combining is as follows:

$$
P_\Sigma \big|_N = \frac{1}{N} \left(\sum_{i=1}^{N} \sqrt{P_i} \right)^2
\tag{4}
$$

where P_Σ is the transmitter output power (summed) and subscript N denote the quantity of power sources.

2.3 Benefits
The use of power combining techniques allows, first of all, to replace a TWT transmitter and not to suffer from its disadvantages. The main advantage is the reliability. A transmitter with many power sources will still emit some power, when a number of them are damaged. The detailed analysis of this effect is presented in Chapter 3 (also Rutledge et al, 1999).
The structure often used consists of power submodules, each containing power transistors, an input power splitter and an output power combiner. It may be configured in distributed amplifier concept, with power submodules placed along the waveguide. The solutions with separate power submodules, exhibit several substantial advantages. Due to their extended metal construction they have an excellent heat transfer capability, which makes cooling easy to perform. Furthermore, they provide an easy access to amplifying units in case they are damaged and need replacing. Finally, once the structure is made, it can be easily upgraded to a higher power by replacing the amplifying units with new ones with a higher output

power. Another way is to stack several transmitters with the use of standard waveguide tree-port junctions.

However, the disadvantage of waveguide distributed amplifiers concerns the frequency band limitation due to spatial, wavelength-related periodicity. The working bandwidth decreases when the number of coupled amplifying units is increased. Hence, there is a power-bandwidth trade-off.

The process of summing the output power from a number of power amplifiers has its inherent advantage. As far as multi-transistor amplifier is concerned, there is always the question to the designer whether to use lower number of higher power amplifiers (transistors) or higher number of lower power amplifiers. Intuitively, one is inclined to use the newest available transistors with maximal available power.

However, taking into consideration that every active element generates its own residual phase noise, the phase noise at the output of combiner is a function of the number of elements. Assuming, that the residual phase noise contributions from all the amplifiers are uncorrelated, then the increase of the number of single amplifiers causes the improvement of output signal to noise ratio (DeLisio & York, 2002).

For a fixed value of output power in a spatial power combining system the increase of the number of single amplifiers gives the increase of intercept point IP3 and spurious-free dynamic range SFDR.

The real advantage of using a spatial combiner is that the combining efficiency is approximately independent of the number of inputs. Then, for given insertion losses of a basic two-input combiner there is a number of power sources (input ports for multilevel combiner) where a spatial power combiner (naturally, with its own insertion losses) becomes more efficient.

In real cases, efficiency of any combiner is limited by channel-to-channel uniformity. Gain and phase variations, which arise from transistor non-uniformities and manufacturing tolerances, can lead to imperfect summation of power and a reduction in combining efficiency. However, considering that the variations of gain have statistical behavior the use of higher number of inputs enables one to average and then minimize the influence.

On the other hand, the variations of phase shift between summing channels have a crucial influence on the output power of the combiner. In the case of multilevel combiner, the phase variations of individual two-input combiners may accumulate and therefore degrade power summing efficiency. Moreover, taking into account that the amplifying modules may have their own phase variations, introducing individual tuning for two-input combiners, becomes extremely difficult for real manufactured systems. In the case of spatial combiner, it is possible to introduce individual correcting tuning for each summing channel (arm). For a higher number of channels, the tuning becomes demanding, yet still possible to be made. It is worth developing an automatic tuning system, involving a computer with tuning algorithm and electronically driven tuners, for example screw tuners moved by electric step motors.

3. Power degradation

3.1 Combined power dependence in case of input sources failures

The output power degradation mechanism in a tree structure is the same as in the spatial one. It may be derived from S-matrix calculations for various numbers of active ports.

Assuming equal input power P_{in} on each of the input ports the relationship for the output power vs number m of non-active ports is expressed as:

$$P_\Sigma|_{N-m} = \frac{P_{in}}{N}(N-m)^2 \tag{5}$$

where m equals from 0 to N.

It may be derived from the analysis of dependence of output wave b_n versus varying number of input waves (a_1 to a_{n-1}) equal to zero.

It means that for a two-input basic network a failure of one of input power sources P_{in} will result in $0.5P_{in}$ output power. Compared to power of $2P_{in}$, available when there is no failure, the penalty equals 6 dB.
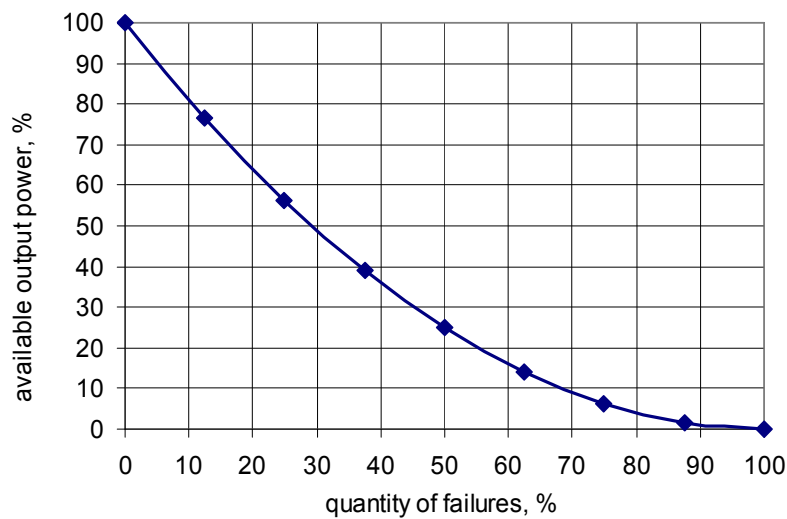
Fig. 3. Combined output power vs number of failed input sources

The power degradation is calculated as the ratio of max output power without failures (when $m=0$) to power expressed as a function of m for different number of sources N.

$$\frac{P_\Sigma|_{N-m}}{P_\Sigma|_N} = \left(1 - \frac{m}{N}\right)^2 \tag{6}$$

where P_Σ is the transmitter output power (summed) and subscripts $N-m$ and N denote the quantity of working modules.

A graphical illustration of Eq (6) is shown in Fig. 3, where the quantity of failures is defined as m/N and expressed in percentages.

3.2 Influence of power degradation on radar cover range

Information presented here is necessary to predict radar range suppression as the function of failures in its solid-state transmitter. The transmitter output power degradation vs number of damaged power modules is given by Eq (6).

Considering the radar range equation and assuming that the received power is constant, in order to achieve proper detection for the same target, the suppression of the range R may be expressed as:

$$\frac{R|_{N-m}}{R|_N} = \left(\frac{P_\Sigma|_{N-m}}{P_\Sigma|_N}\right)^{1/4} = \left(1 - \frac{m}{N}\right)^{1/2} \tag{7}$$

Here R is the radar cover range and subscripts N-m and N denote quantity of working modules.

It may be seen that for 50% of modules failed, radar coverage decreases to 70% of its maximal value (Fig. 4).
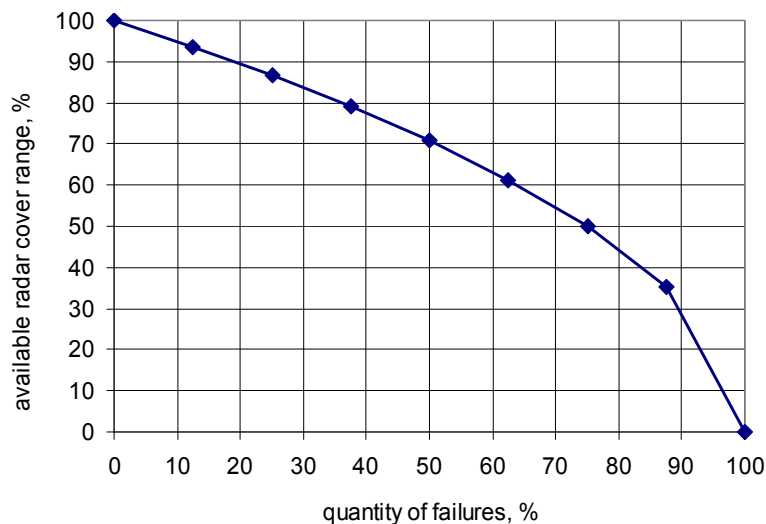
Fig. 4. Radar cover range vs. number of failed input sources

All these considerations assume perfect matching and isolations between channels in spatial power combiner. In real case, the isolations are not ideal and a failure of power transistor might result in different output impedance thereof, from open to even short circuit. Therefore, the real output combined power may differ from the ideal one.

4. Examples of multi-input splitters/combiners

The need for replacing TWT high power amplifiers in higher frequency bands contributes to the invention of new methods of power combining from many single semiconductor amplifiers. Those already known that involve planar dividers/combiners based on Wilkinson or Gysel types offer noticeable power losses in higher bands (X, K) especially when used as complex tree-structure for combining power from many basic amplifying units. The methods of spatial power combining may be divided into two main ideas. The first method is to place a two-dimensional matrix of amplifier chips with micro-antennas inside a waveguide. The second comprises the use of separate multiport input splitter and output combiner networks. It employs the use of specially designed structures (Bialkowski

& Waris, 1996; Fathy et al, 2006; Nantista & Tantawi, 2000; Szczepaniak, 2007; Szczepaniak & Arvaniti, 2008) or a concept of distributed wave amplifier, where amplifying units are coupled with input and output waveguides by means of a set of probes inserted into the waveguides.

4.1 Waveguide built-in 2D array of amplifiers

The solution presented here may be regarded as a technique of so called quasi-optical power combining. Quasi-optical method of power combining assumes multidimensional diffraction and interference of incoming and outgoing waves at input and output of a power combining system. The most typical example of such a solution is two-dimensional matrix of amplifiers, each with mini-antennas at their inputs and outputs (Fig. 5). The 2-D amplifying matrix may be inserted into a waveguide (sometimes oversized) or illuminated by means of a horn antenna, additionally with dielectric lenses. The second horn antenna collects output power from all the transistors. There are many technical examples of the amplifying grid construction and splitting/combining structures (Belaid & Wu, 2003; Cheng et al, 1999-a; ; Cheng et al, 1999-b; Zhang et al, 2007).
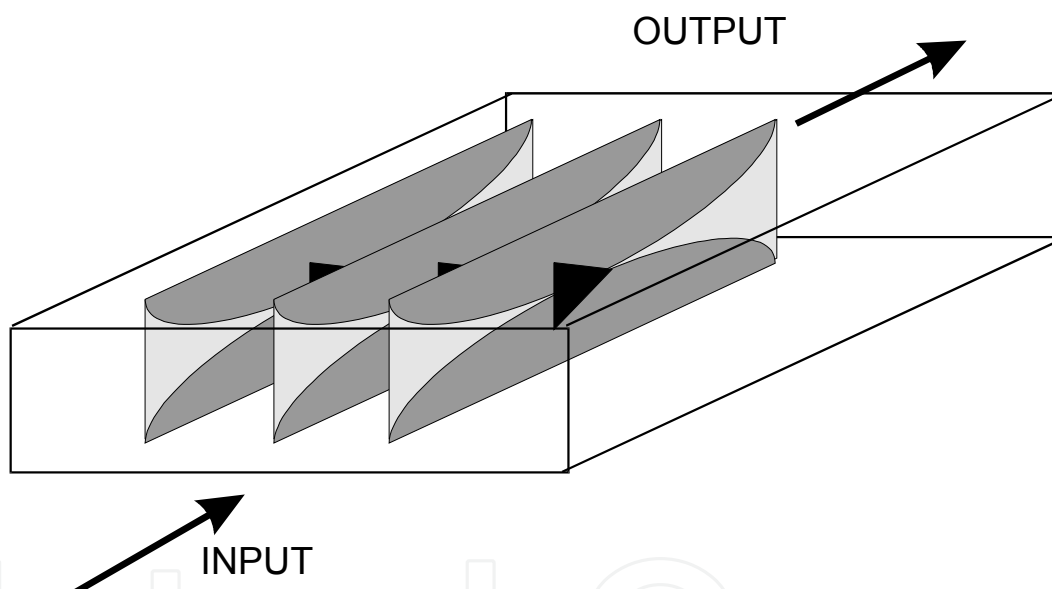

Fig. 5. Concept of waveguide built-in array of microantennas connected to amplifiers

A grid of amplifiers may contain even several hundred of active devices. In the case of insertion 2-D amplifiers set into a waveguide, the input antennas matrix probes the E-M field distribution inside the waveguide. After amplifying, the output antennas matrix restores field distribution and excites a wave going towards the waveguide output. The whole structure may be regarded as a section of an "active" waveguide. The main development is being done in the concept and structure of a transistors array. The transistors may be placed on the plane (in real case dielectric substrate) perpendicular to the waveguide longitudal axis (called grid amplifiers), or they may be stacked in sandwich-like structure, where layers are parallel to the waveguide longitudal axis (called active array amplifiers).

The main advantage of waveguide built-in concepts is their compact structure and wide frequency bandwidth of operation. However, there are some disadvantages, for example,

difficult heat transfer, especially when high power is desired, the necessity of special simulation and design, and inconvenient repairing.

4.2 Distributed waveguide splitter/combiner

The most frequently used structure of distributed splitter/combiner scheme assumes the use of hollow waveguide, e.g. rectangular one working with H_{10} mode, with a number of probes inserted into the waveguide and periodically distributed along its longitudal axis. The period equals half-wavelength of guided wave $\lambda_w/2$ at the center frequency. The waveguide is ended with a short, which is at quarter-wavelength distance from the last probe. The structures of the splitter and the combiner are identical. The differences between subsequent solutions are in the concept of EM field probes (Bashirullah & Mortazawi, 2000; Becker & Oudghiri, 2005; Jiang et al, 2003; Jiang et al, 2004; Sanada et al, 1995).
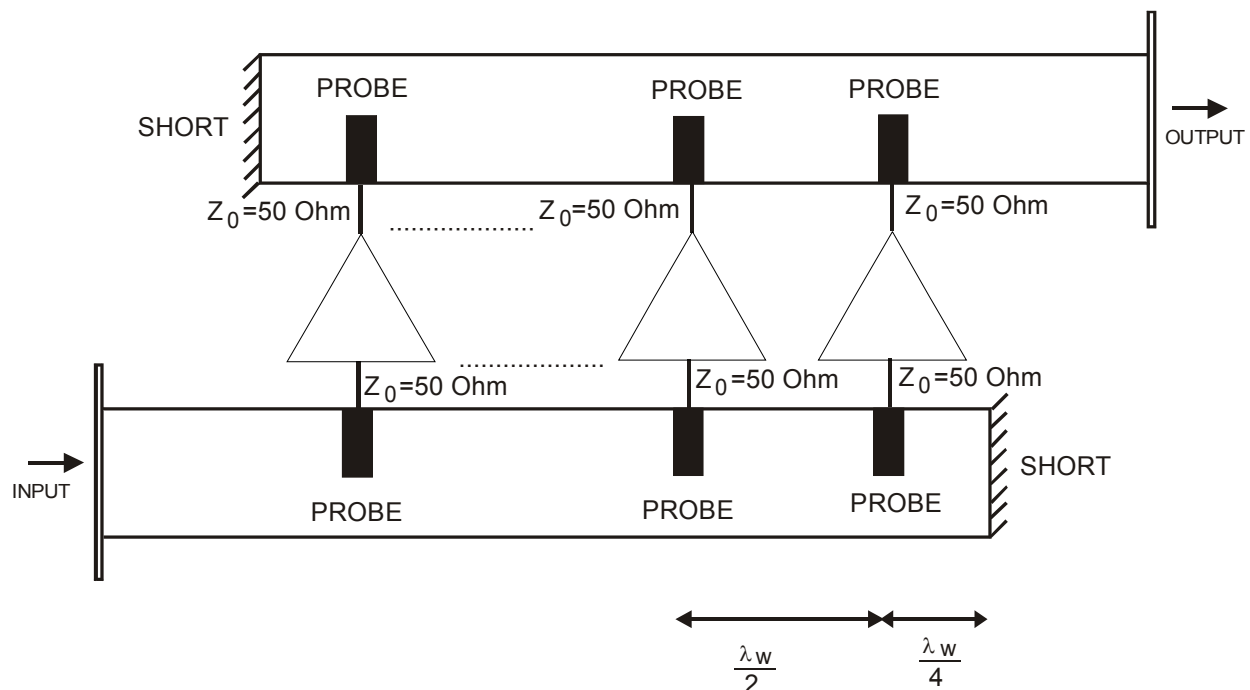

Fig. 6. Concept of distributed waveguide power amplifier

For the centre frequency the short-ended section of the waveguide is transformed into the open-circuit and the half-wavelength sections of waveguide transforms adjacent probes impedance with no changes. Therefore the equivalent circuit of the splitter contains N probes impedances in parallel connected to the input waveguide impedance. Each probe transforms the 50 Ohm impedance of the amplifier into the value required to obtain equal power splitting ratio from circuit input port to each of the output. Spatial distribution of the probes along the waveguide causes frequency dependence of power transmission to each probe. As the result for increasing number of outputs (probes) the frequency band of splitter/combiner operation becomes narrower.

The simplest solution is a coax-based probe inserted through a hole in the wider waveguide wall. The length of the probe, its diameter and distance from the narrow waveguide sidewall results from design optimization for minimal insertion losses and equal transmission coefficient for each channel.

There are many solutions for the probe design, for example, it may be a microstrip line with a piece of substrate laminate inserted into the waveguide, or specially designed slot in the wider waveguide wall, coupled with a planar circuit on the laminate with ground metallization removed.

An example of application of four amplifying modules connected to four-probe waveguide splitter and combiner is shown in Fig. 7 (Szczepaniak et al, 2009).

Fig. 7. Example of power amplifier using five-port distributed waveguide power splitter/combiner

4.3 Four-input microwave rectangular waveguide combiner

The four-input waveguide splitter, according to this concept, offers a very high working bandwidth and low insertion losses, providing a good reason for the design of solid-state high power modules. The concept of construction may be applied to any rectangular waveguide, in frequency band related to its dimensions.

The example structure shown below is assumed to work in X-band (Szczepaniak, 2007). It is based on a standard X-band rectangular waveguide R-100 with a short at one end. The input port for the splitter is the waveguide and the four output ports are of 50 Ohm coaxial type. The cross-sectional diagrams of the discussed structure are shown in Fig 8.
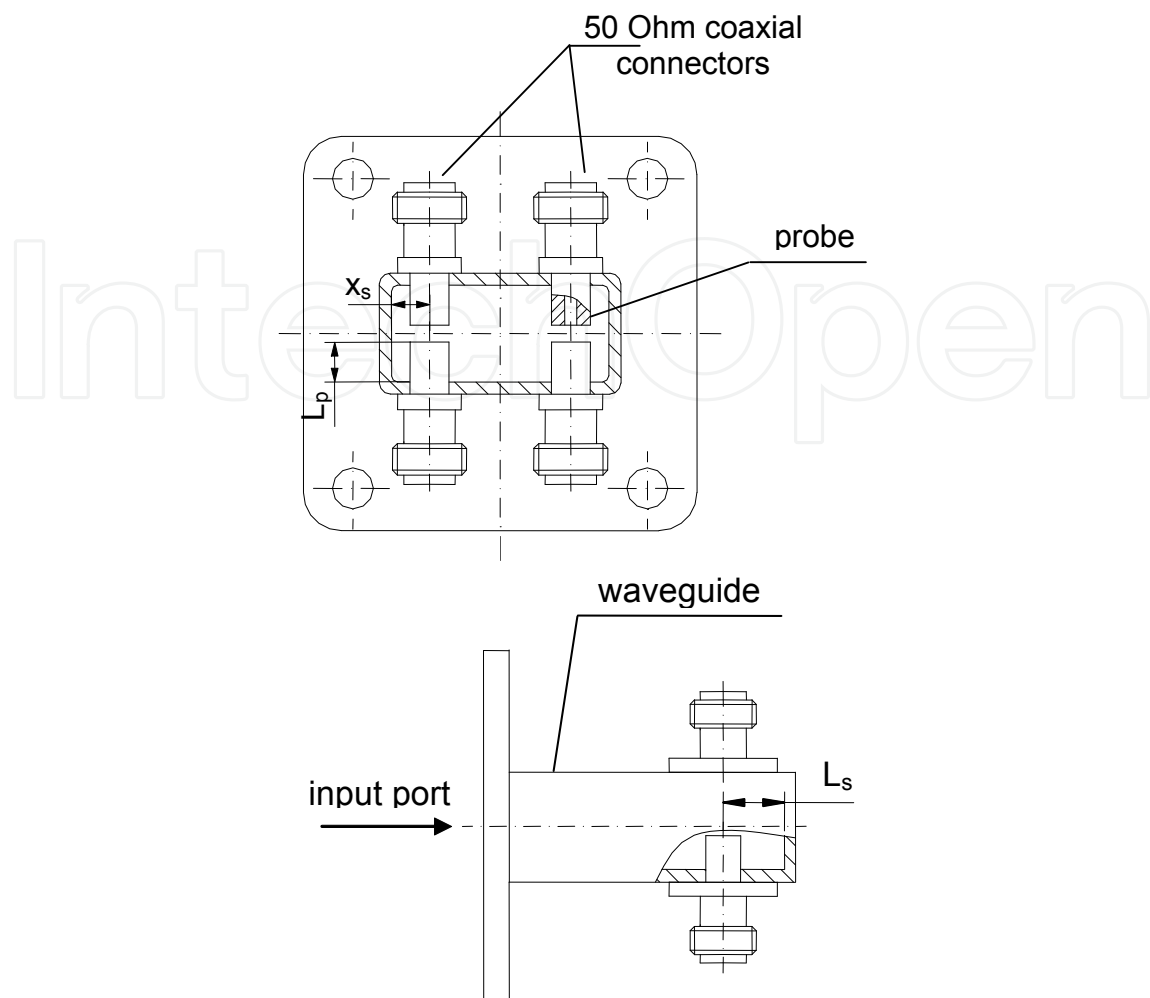
Fig. 8. Five-port waveguide splitter/combiner

The coupling is performed by means of four coaxial probes, made from 50 Ohm coaxial line with the outer conductor removed. The probes are inserted into the waveguide in the plane, at a certain distance L_S from the shorted end.

In order to achieve four-way equal power dividing and avoid reflections, the equivalent impedance in the plane of the probes insertion must equal wave impedance Z_w. As the four probes are connected parallelly, each one should be regarded as the impedance four times higher than that of the wave. The probes are connected to further microwave devices, e.g. amplifying modules, which have input/output reference impedance Z_0=50 Ohm. Therefore, each probe must work as an impedance transformer from value Z_0 to $4 \cdot Z_w$ (Eq. 8)

$$Z_{probe} = 4 \cdot Z_w = n^2 \cdot Z_0 \tag{8}$$

where n is the equivalent transforming ratio, which fulfills the condition (8). This is a simplified case and it can be assumed for the ideal transforming probes and a single frequency. In such case, the presence of a quarter-wavelength section of the waveguide and its frequency dependence can be temporarily neglected. The situation is shown in Fig. 9
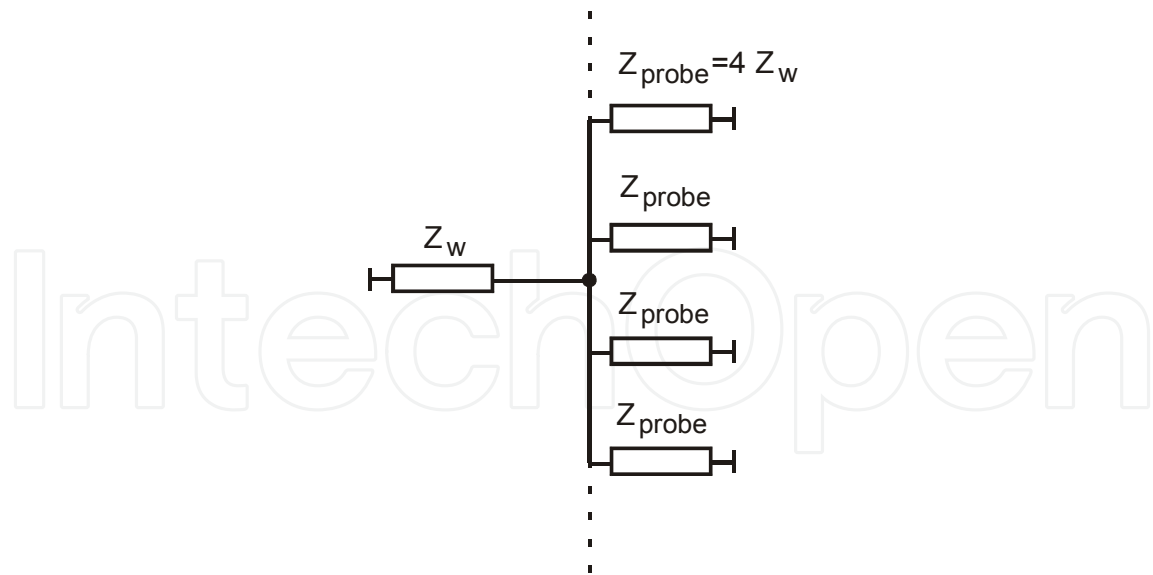
Fig. 9. Simplified equivalent circuit of four-probe splitter at centre frequency

The length of the probe L_p and the distance x_s (Fig. 8) from the lower waveguide wall are the parameters to be optimized in order to obtain a wide frequency bandwidth where the input reflection coefficient is as close as possible to the desired value. Furthermore, one can begin the design of the power splitter from the design of one probe which fulfils the condition (8). In such case, the starting point of the design is a section of the waveguide with length equal to the odd number (2m+1) of quarter guided wavelength λ_w, as shown in Fig.10.
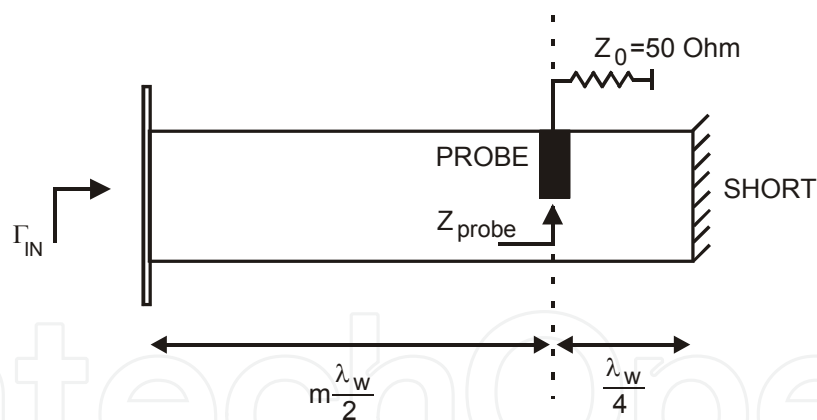
Fig. 10. Configuration of one probe inside a waveguide

After one probe has been optimized fully, a four-probe circuit is to be simulated. The pre-optimized probes are inserted symmetrically with respect to the main longitudal axis of the waveguide. Next, the second issue must be considered. Inserting the probes into the waveguide causes disturbance of the field distribution, excitation of higher order modes, and, therefore, creates additional parasitic susceptances which add to the admittance seen via the probe. As a result, the final stage of design concerns simulation of four pre-designed probes with the shorted section of the waveguide. The optimization of the probe's parameters (the same as before) together with the length of the shorted waveguide section gives the final matching of susceptances in the plane of probes insertion. This way it is

possible to obtain broadband matching, which gives a wide frequency range of a very low reflection coefficient for full power splitter and flat transmission to each of four outputs approaching to ideal value of -6dB.

The splitter structure proposed here has an interesting additional feature. The transmission from the waveguide port to the coaxial ports placed on one of the wide waveguide walls differs in phase from the transmission to the ports on the other wide wall. It is because the probes are inserted in parallel to the lines of the electric field of H_{10} mode. The phase difference equals π. Due to the fact that all the probes are inserted close to each other without any additional shielding, which may be additionally considered, the values of the isolation between them are not high. This is about -3dB for opposite probes (between wide walls) and about -10dB for adjacent probes (on the same wide wall).
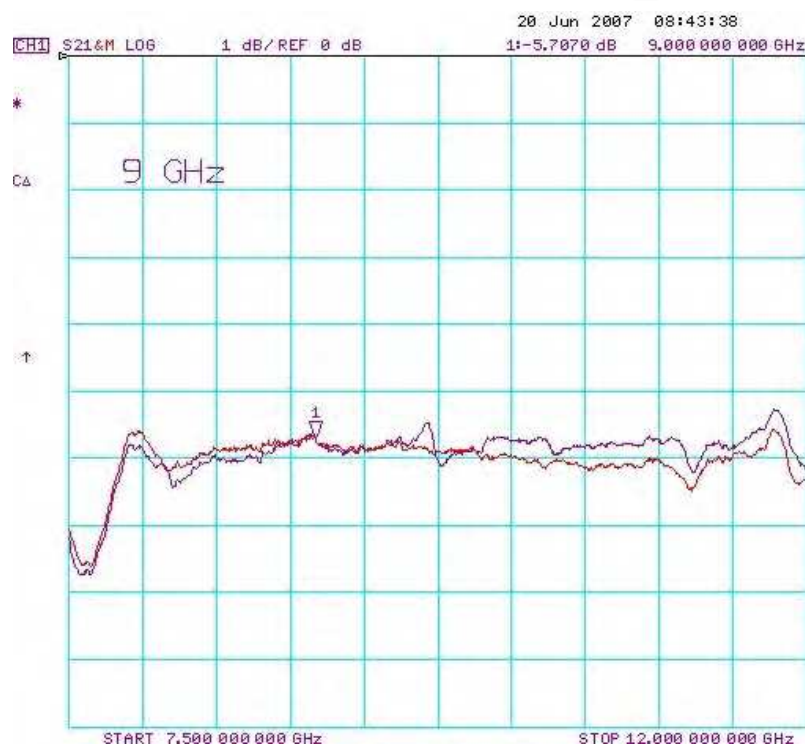

Fig. 11. Example of measurement results – transmission characteristics from waveguide to coax ports for two coax outputs

The structure of the four-way power splitter shown here offers a frequency bandwidth many times wider than an equivalent, four-way distributed waveguide structure. It may be used together with standard waveguide T-junctions in order to achieve simple eight-way power splitter by connecting two of them. Such a structure will still have wider bandwidth than a distributed wave one. The insertion losses are sufficiently small, about 0.2÷0.3 dB, and the input reflection coefficient is low enough to make this splitter an attractive alternative to distributed waveguide structures. There is a phase difference, equal to π between transmissions from waveguide port to outputs placed on the opposite wider walls of the waveguide, which may be useful in some measurement applications. The proposed structure is also very simple. And finally, although it has a relatively low isolation between output coaxial ports, in the case of symmetrical power combining, when the amplifiers are designed to have good matching to 50 Ohm, this power splitter/combiner works properly.

An example of application is shown in Fig. 12 (Szczepaniak et al, 2009). Here four amplifying modules are connected to two identical splitting/combining structures.
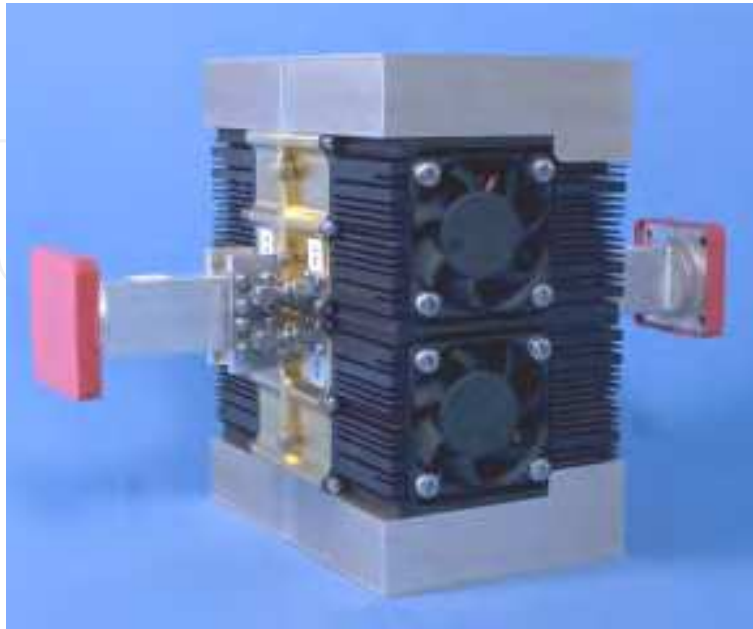

Fig. 12. Example of high power X-band amplifier using four-input rectangular waveguide power splitter and combiner.

4.4 Eight-input microwave circular waveguide combiner

The following splitter structure comprises a section of cylindrical microwave waveguide and nine coax-based probes (Szczepaniak & Arvaniti, 2008). The waveguide has two circular walls which transform the waveguide into a resonator. The input probe is inserted in the center of one of the circular walls and the remaining eight probes are inserted into the second circular wall. The probe insertion points form a circle, whose center corresponds to the center of the second wall.

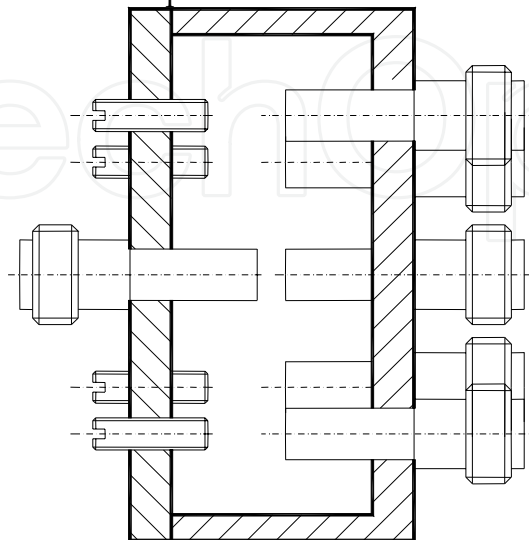The cross-section and 3D view of the splitter structure are shown in Fig. 13 and 14.

Fig. 13. Nine-port circular waveguide power splitter/combiner

In order to provide tuning possibility for all the output probes eight screw tuners are inserted in the wall containing the input probe. The tuners are placed according to the positions of the output probes but on the opposite wall.

All the probes are made as sections of 50 Ohm coaxial line with outer conductor removed from the part inserted inside the cavity. In this case special coaxial jacks from Radiall containing special Teflon-covered pin with diameters corresponding to a 50 Ohm line have been used.

The inner cavity dimensions and probes placement are optimized to obtain minimal input reflection coefficient and uniform power division. Each of the probes transforms 50 Ohm line characteristic impedance to a value loading the cavity. Symmetrical probe insertion gives symmetrical field disturbance and distribution. Careful design gives optimal power transfer from center probe to eight output probes and vice versa.

The number of output probes may be different. It depends on a designer's needs. The key factor is to control the field distribution inside the cavity during the design process. For each desired number of inputs the optimization procedure gives the dimensions and positions of the probes and the dimensions of the cavity.

Fig. 14. Manufactured model structure of nine-port power splitter/combiner

This example structure is designed to work in X-band. Assuming that the working bandwidth is defined by 0.5 dB drop of transmission coefficient, the obtained bandwidth is equal to about 8.3-10.7 GHz. Within the working bandwidth, all the measured characteristics fall within the range -9 dB +/- 0.5 dB. Depending on the application, the useful working bandwidth may be defined differently, for example on the basis of 1dB-drop of the transmission.

For purposes of power combining from microwave amplifiers the combining losses should be as low as possible. The test structure presented here does not have silver or gold plating inside the cavity, therefore, the insertion losses may be decreased further. The input reflection coefficient has an acceptable value lower than -10dB within the working band.

An example of measurements results for the test structure of the splitter is shown in Fig. 15.

Fig. 15. Example of measurement results – transmission characteristics from centre coax input to one of coax output port

5. Conclusion

Solid-state power sources based on spatial power combining may successfully replace TWT central transmitters. This method of power combining offers several advantages compared to the use of multi-level three-port based approach. In high power transmitters it is important to reduce the combining losses to as low as possible. Spatial combining does not suffer from additive accumulation of insertion losses and phase mismatches of individual devices as in the tree-structure of cascaded two-input combiners, which is the reason why it is very promising.

In case of failures of power transistors, solid-state transmitter exhibits soft output power degradation. The radar coverage, which may be calculated for a given number of working modules, reduces softly while failures proceed. It, therefore, gives additional reliability to radar systems using power sources based on spatial combining.

According to most recent developments, in the case of single transistor/semiconductor amplifiers, we are approaching the limits of power density and combining efficiency. On the other hand, combining large numbers transistors on-chip eventually becomes impractical. It results in most of the semiconductor area being occupied by the passive matching and combining circuitry. Furthermore, losses in the semiconductor transmission lines are relatively high. These factors limit combining efficiency. In order to realize solid-state components with higher power and efficiency, new kinds of combining techniques have to be used. They should integrate large numbers of devices with minimal signal splitting and combining losses. Additionally, the desired amplitude and phase relationships between summing channels should be maintained. Spatial or quasi-optical techniques provide a possible solution. Additionally they give promising phase noise degradation for power transmitter.

The future challenges are as follows: critical power in one combiner (to avoid discharge or damage of a probe), effective cooling and heat transfer from individual power transistors, automatic failure detection and current temperature sensing, easy access to repair, or finally application of automated tuning procedures and circuits for testing and output power optimization.

6. References

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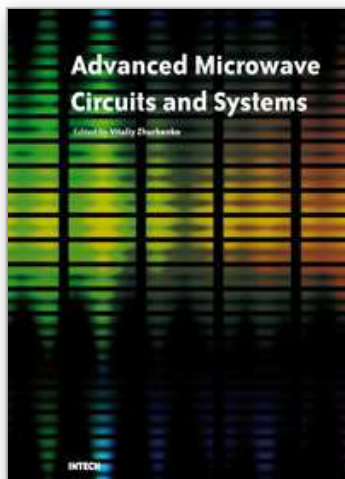
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