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INTRODUCTION

Butler matrices are fundamental elements in multi-port power amplifiers (MPAs). In a MPA, the individual RF input signals are distributed by an input Butler matrix to feed all the amplifiers, while a high power Butler matrix combines the amplified portions of the assigned signal into a single output port.

The main advantage of the MPA is flexibility of the power allocation among the single amplifiers and a better absorption of traffic in case of failure of one of the high power amplifiers (HPAs).

The Butler matrices traditionally used for MPAs are mainly implemented with several hybrid couplers providing broadband responses. The critical points for the classical implementations are the phase balance between the output ports and the manufacturing complexity since multiple cross-connections might be required. Extra filters are commonly placed after the high power Butler matrix to ensure the suppression of interfering/unwanted signals.

Lately, novel synthesis methods and physical implementations of a new Butler matrix solution have been presented. These are based on coupled resonators and provide simultaneously signal distribution and frequency selectivity. Thus, required filter functions for the suppression of interfering signals can be imposed on the Butler matrix to avoid the need of extra filters.

The assessment of this new class of distribution network must be performed at payload level where all the required filter functionality can be seen. Since the novel solution is incorporating a level of rejection (which can be selected by design) the design of additional filters can be simplified. In those cases where the required rejection can be met by the novel Butler matrix solution, no additional filters will be required. This will have a significant advantage in terms of size reduction compared to the traditional approach consisting of a distribution network plus a bank of BPFs.

This paper will summarise the different solutions and implementations developed so far. Low and high power designs will be presented based on SIW and waveguide technologies.

TRADITIONAL PAYLOAD ARCHITECTURES

The architectural design of satellite communication payloads (especially those for mobile satellite communications) has benefited in terms of flexibility, from the adoption of Multiport Power Amplifiers (MPA's).

The first reference to the basic idea of a Multiport power amplifier dates back to the invention of the Butler multiport network in 1960 [1], although the application of MPAs to satellite transponders was first envisioned at Comsat Laboratories in 1974 [2]. The first practical application of the MPA concept to satellite communications came many years later, when it was adopted by Nippon Telephone and Telegraph Company (NTT) from the S-band mobile communications payload on board the experimental Japanese satellite ETS VI. After an intense R&D activity on MPAs applied to antenna architectures performed by ESA [4], MPA-based configurations were then adopted on board the Artemis satellite (L-band payload), and on the Inmarsat III, Inmarsat IV [3] and Alphasat satellites.

The payload configuration where each high power amplifier is connected to a single feed has several inconveniences. The main drawbacks of such configuration are related to failure mechanisms and traffic allocation. Firstly, the failure of one high power amplifier (HPA) might lead to the total loss of one beam, unless appropriate redundancy schemes are adopted (mainly based on redundancy switches). Secondly, the share of the total traffic capability that can be handled at individual beam level is limited by the maximum output power provided by the single HPA connected to the feed. When unequal traffic demands exist, this configuration is not capable in dealing with the required increasing of power in order to increase the traffic capability.

A front-end configuration based on a Multiport Power Amplifier can solve, to a great extent, all the problems mentioned. In the MPA architecture, the input signals are equally distributed among identical HPAs operating in the linear region. In this case, all the amplifiers share all the signals. Later, all the signals coming from the amplifiers are reconstructed in order to avoid interference. This initial split of the input signals is performed by a Butler matrix, also called input network (INET). The phase distribution provided by the input Butler matrix is exploited in order to, theoretically, re-obtain the same initial signals, but amplified at the output. The recombination network is cascaded with the power amplifiers and is also called the output network (ONET). In this way all amplifiers contribute to each individual beam; the failure of one HPA does not cause the total loss of one beam (although a non-negligible reduction in RF output power occurs). It is also possible to cope with variable traffic demands. An example of MPA architecture and in-operation system implementing the MPA is shown in Fig.1. Additional redundancy mechanism can be implemented inside the MPA.

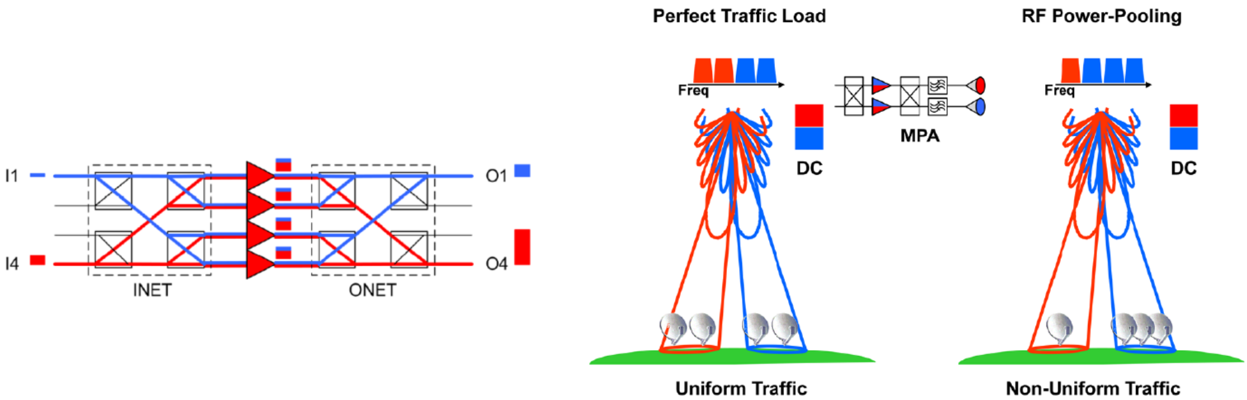

Figure 1 (a) Basic MPA (4by4) operation (b) Flexible Allocation of Power

Possible drawbacks deriving from the adoption of MPAs are the presence of post-HPA losses in the output hybrid matrix and the need for the power amplifiers to work in multicarrier operation, which makes MPAs less attractive in single-carrier-per-beam applications.

As an example, L-band Multiple Port Amplifiers (MPA) have been used for the Inmarsat satellites. Such satellites have allowed for greater flexibility, increased bandwidth, more channels and hence greater capacity as well as frequency colour re-use.

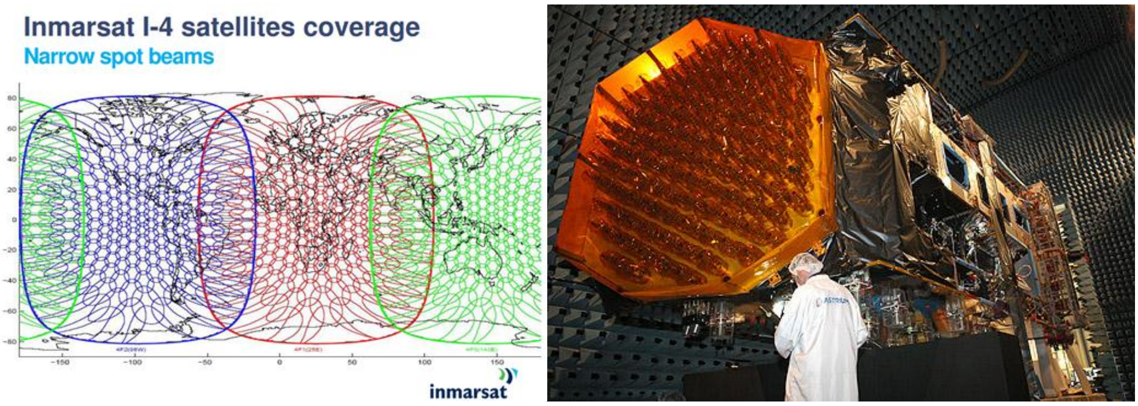

Figure 2 (a) Inmarsat coverage I-4 Americas, Alphasat and I-4 Asia-Pacific (b) Alphasat satellite

The output power section operates by generating a set of signals of defined amplitude and phase within the DSP at an IF frequency. These are then transmitted through the Post-Processors which up-convert to L-band and are amplified and filtered prior to being sent to the MPAs. Within the MPA the low power signals are split within the INET and amplified to become high power signals prior to being recombined within the ONET. The amplified signals are then all sent to the array-fed reflector antenna where they form a spot beam on the earth.

The Butler matrices proposed in the literature for MPAs are mainly implemented with several hybrid couplers based on transmission lines, producing a relatively broadband response.

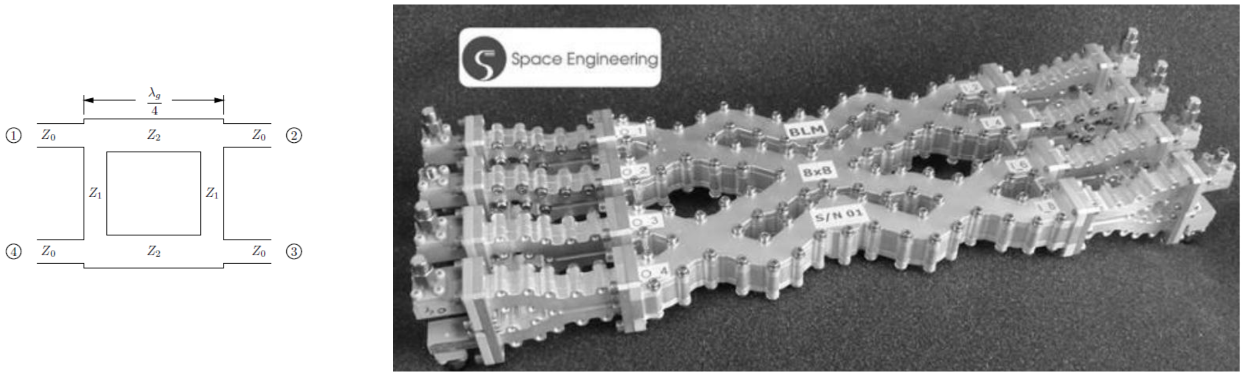

Figure 3 (a) Fundament building block (b) Ka-band 8x8 butler like matrix [5]

If it is required to suppress the spurious frequencies or the intermodulation products generated by the HPAs, separate bandpass filter (BPF) or low-pass filter (LPF) interfaces need to be cascaded to the ONET, as shown in Fig. 4(a). This configuration has been adopted in various telecommunication satellites for S- and L-band [6]. The extra filters lead to bulky equipment, which can be of critical importance, especially in satellite applications where there are stringent constraints in the size and mass of the on-board devices.

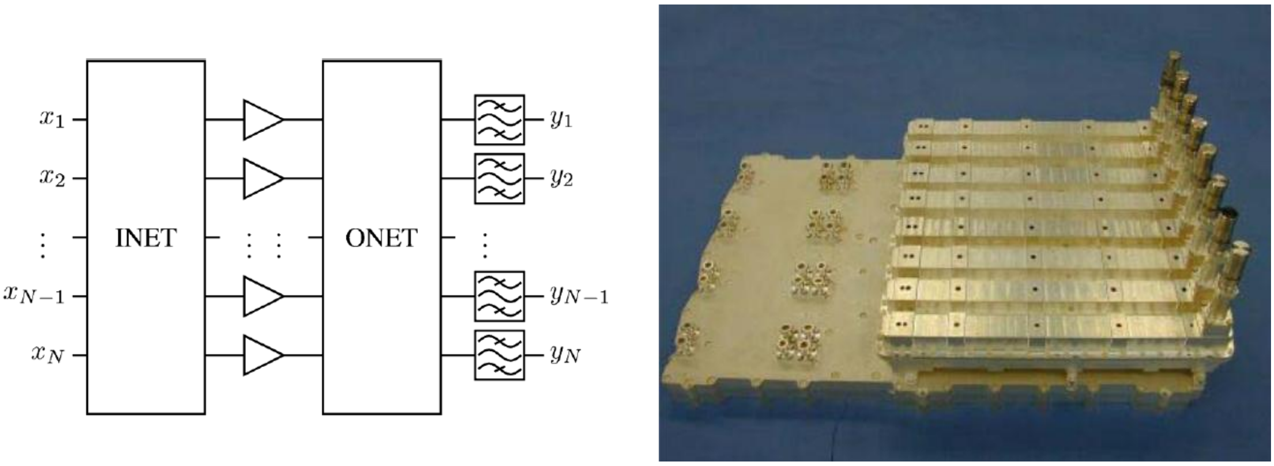

Figure 4 (a) MPA with BPFs cascaded (b) ONET + BPF [6]

NEW CLASS OF SIGNAL DISTRUBUTION NETWORKS

In recent years, solutions to incorporate the bandpass filtering function and the Butler matrix into one single circuit based solely on coupled resonators have been developed [7-13]. The new Butler matrix that includes all the filter transfer functions will substitute the ONET plus BPFs, resulting in sensible size and mass reduction. Fig. 5 is a representation of the MPA that includes the ONET with inherent BPFs. A general and analytical synthesis technique of the coupling matrix of Butler matrices with an inherent filter function (Chebyshev or Butterworth) based on resonators was presented in [7]. The synthesis is based on a main building block, a 180 degree coupler.

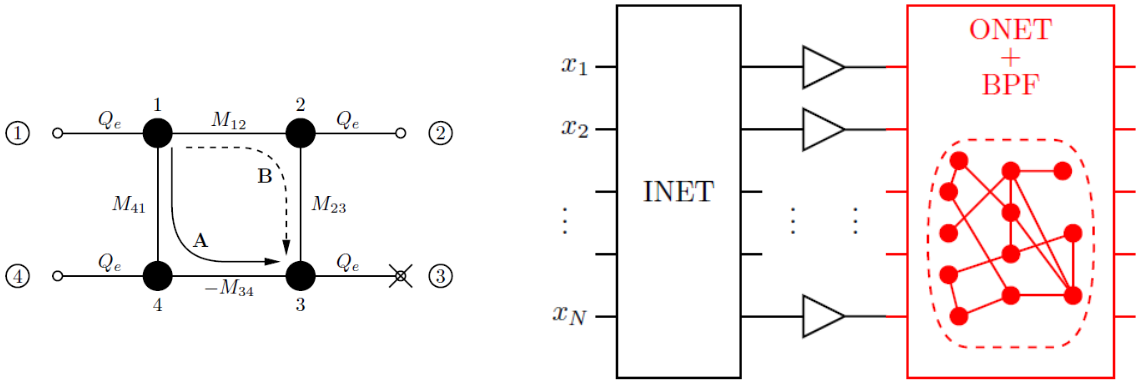

Figure 5 (a) Fundamental building block (b) ONET + BPF [7]

Fig. 5 shows the schematic of a 180 hybrid coupler based on coupled resonators. Black circles are resonators with the electromagnetic (EM) couplings represented here by lines. The network shows the response of a typical rat-race coupler with a two-pole filtering characteristic. All the coupling coefficients are the same, except for the one between resonators 3 and 4, which has the same magnitude, but with opposite sign. In resonator 2 there exists a totally destructive combination of signals from paths A and B that generate the perfect isolation at port 2. This provides a virtual open circuit at resonator 2 when considering paths from ports 1 to 3 and from 1 to 4 [14]. The network exhibits two identical filter functions, with two poles each, while the network has four resonators.

The overall design of multi-port combiner networks considers convenient interconnections of several single/individual power-combiner components. It is possible to implement transmission zeros directly at synthesis level by considering additional resonator subsections (topologies), directly coupled to the basic building block (to satisfy specific rejection requirements).

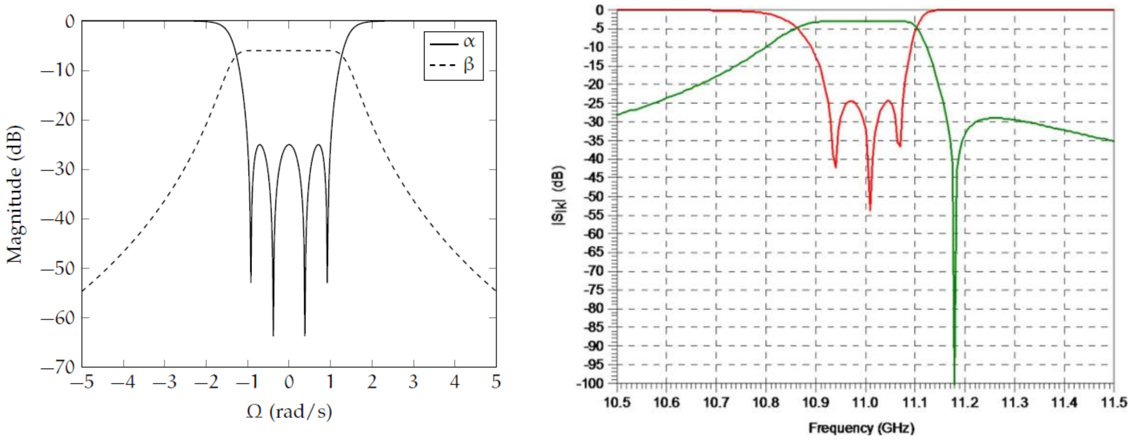

Figure 6 (a) Synthesis of 4X4 butler matrix (b) transmission zeros implementation

Once the topology and coupling values are defined, the technological implementation can be based on multiple resonator configuration (combline, planar, waveguide, SIW, etc.). As examples, two implementations are reported in fig 7 and fig 8 . Further information can be found in [7] and [8] respectively. The RF measurements compared to the theoretical curves, show good match.

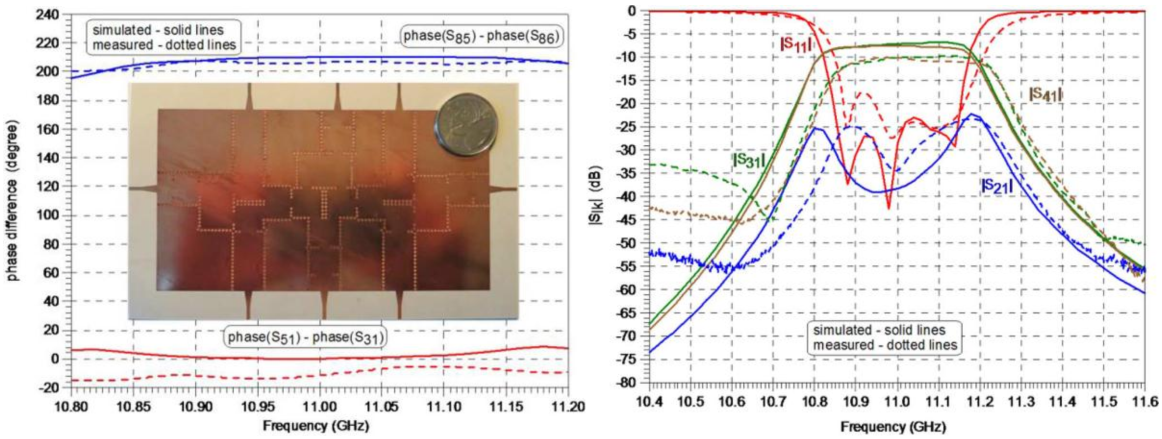

Figure 7 (a) Eight ports SIW prototype (b) RF performance

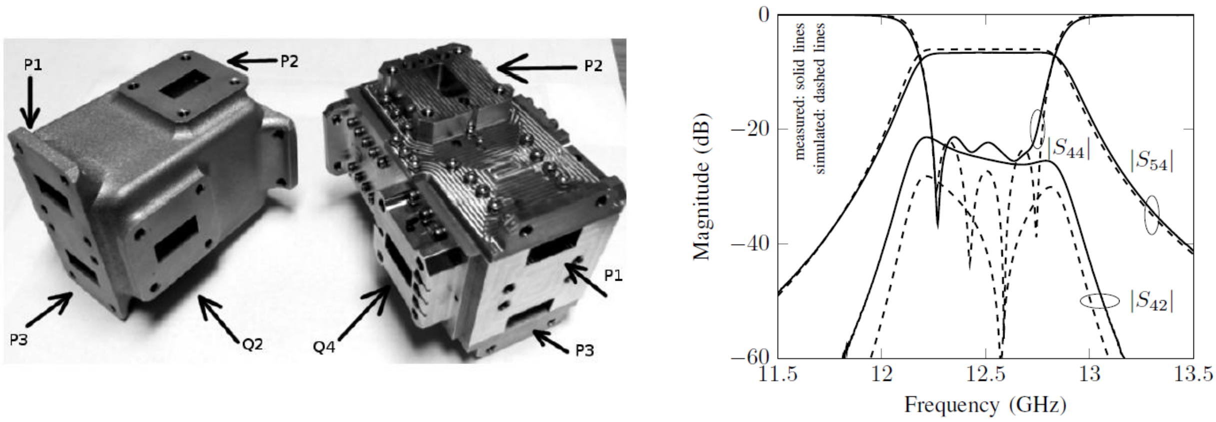

Figure 8 (a) 4X4 waveguide prototype (b) RF performance

PAYLOAD IMPACT

Consider a traditional Butler matrix formed by 90 degrees or 180 degrees branch line couplers which are cascaded with BPFs of n-poles each (one filter per output). A defined number of cavities are necessary to obtain the required selectivity. The advanced Butler matrix proposed here incorporates both the distribution/power divider network and the filtering selectivity. These properties are achieved through a circuit based only on coupled resonators, which, without any external additional resonator, produces a filter function of poles per output; e.g., a 4x4 Butler matrix will be realized from 20 resonant cavities, providing 4-order filter functions between all input and output ports. The same performance in terms of selectivity and power distribution are obtained by the proposed Butler matrix, making redundant the ONET based on transmission lines. The saving is the space occupied by the distribution network.

The architecture of the MPA of Fig. 4(a) can be modified with the proposed solution substituting the ONET cascaded by BPFs. This leads to a more compact configuration with four inputs/outputs. The example has been synthesized for a conventional 4x4 ONET with the baseline of a transmission-line Butler matrix and four BPFs of fourth order. The specification considered is f0= 12.5 GHz, bandwidth of 500 MHz, and filters with return loss better than 25 dB (4th order). The circuit has been simulated in standard WR75 waveguide. If no isolators are considered between the Butler matrix and filter sections, the overall volume of the circuit shown in Fig. 9 (a) is 96.7 cm^3. The proposed solution of incorporating the distribution network and filters in a single component leads to a save in volume of more than 30% or more [7].

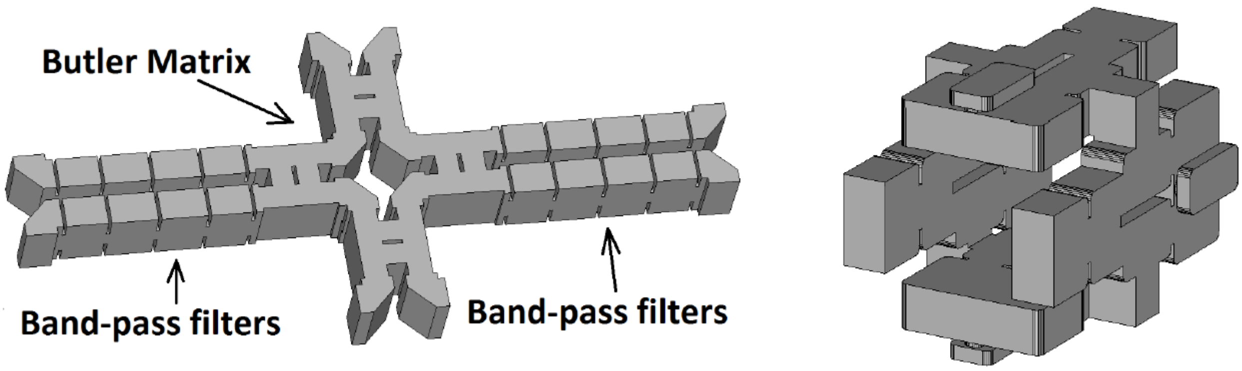

Figure 9 Example of 4 4 MPA. (a) Proposed ONET including the filter functions through a circuit based on coupled resonators and (b) conventional baseline of the ONET with four BPFs cascaded to the transmission-line Butler matrix

CONCLUSIONS

A new Butler matrix that incorporates BPF functions has been presented. The basic principles of these networks, as well as their applications in MPAs, have been discussed and some implementation examples for satellite telecommunication applications reported. The solution solves the need to add filtering selectivity at the output of the ONET in order to suppress spurious frequencies generated by the power amplifiers of the MPA. Normally, extra filters are considered in cascaded to the output Butler matrix. A new circuit based only on coupled resonators is presented, showing both the power division, phase distribution, and filtering transfer function. The advantages in terms of size and mass reduction are a key feature of the present solution. Also, the synthesis presented here is completely general and no assumption has been made over the type of resonator used.

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