Cylindrical Cavity Microwave Power Combiner with Microstrip Line Inputs and Rectangular Waveguide Output

Vinay Ravindra*, Hirobumi Saito**, Jiro Hirokawa*** and Miao Zhang***

*Department of Electrical Engineering and Information Systems, The University of Tokyo, Japan,

**Japan Aerospace Exploration Agency, Japan,

***Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Japan

Abstract — A compact microwave power combiner for combining output from six solid-state power amplifiers is studied. The combiner consists of 6 standard microstrip line inputs from high power amplifier, resonant cylindrical cavity and one standard rectangular waveguide output. The effect of input power amplifier failure is also studied and simulation results are described. Insertion loss of less than 0.3 dB over 200 MHz bandwidth in X-Band is simulated.

Index Terms — Cavity resonators, power combiners, power amplifiers.

I. Introduction

Use of Solid-State Power Amplifiers (SSPAs) in high power applications such as radars is growing in recent years with increase in output power capabilities of SSPAs. There are several advantages of using SSPAs over traditional klystrons, travelling wave tubes (TWTs), and magnetrons, detailed in [1]. The output power capability of SSPA such as GaN HEMTs in X-Band is also growing. Recently Kikuchi [2] reported a 310 W output power capability GaN HEMT in the X-Band. In applications where more power is needed, a power combining technique is necessary to coherently add output power from many similar power amplifiers. Paper [3] gives an overview of microwave power combining techniques and classifies the power combiners into device level and circuit level (corporate structure and N-way).

The purpose of this research is to realize a low-loss microwave power combiner to be used as on-board transmitter for a small satellite synthetic aperture radar system. Small satellites have stringent mass and size constraints which limit use of traditional TWTs. We leverage the advances in X-Band SSPAs and design a low-loss power combiner so that we can utilize the advantages of SSPAs in this high power application. Direct interface of the power combiner to the microstrip line SSPA output, and the output interface to the satellite antenna bus system using WR90 waveguide is achieved, thus reducing potential intermediately losses and making the structure compact.

II. Principles of System Design

The selection of the power combining strategy depends on the system requirements. Our system requirements are listed in Table I. However the requirements are not very unique and are applicable to many applications in real world.

TABLE I
SYSTEM REQUIREMENTS

Parameter	Value
Peak Power	>600 W
Duty Cycle	20%
Frequency	9.55 GHz – 9.75 GHz
RF Input	Microstrip Line
RF Output	Rectangular Waveguide
Power Amplifier	6 x 120 W GaN HEMT

The output power from SSPA is preferred to have a microstrip line interface to the rest of circuitry since both are planar technology. Paper [4] reports X-band 250 W GaN HEMT SSPA in which output of four 80 W GaN HEMT SSPAs are combined using a suspended-line tree structure. They report insertion loss of 0.4 dB and minimum return loss of 20 dB over 9.5 GHz to 10 GHz in simulation. The challenge with this power combining strategy is that, the number of stages of power combining increase with the number of inputs. The number of couplers and connecting transmission lines increase which add loses and significantly degrade combining efficiency [5]. For large number of inputs N-way power combiner which combines power in a single stage is preferred.

N-way power combiners are further classified into resonant and non-resonant power combiners [3]. Non-resonant power combiners have the advantage of allowing broadband operation. Available non-resonant microstrip line power combining strategies such as in [5], [6] use dielectric substrate radial lines, which are relatively lossy compared to waveguide or cavity based power. The output terminal of these power combiners usually consists of microstrip-to-coaxial probe converter.

Since our bandwidth requirement is relatively narrow we have the liberty to choose a resonant power combiner. A resonant cavity combiner was first proposed in [7] which consist of a rectangular-waveguide cavity with coaxial-waveguide inputs along the rectangular waveguide walls. Paper [8] shows design of radial power combiner with circular

TM$_{0m0}$ mode cavity with open-circuited coaxial line terminals. Radial power combiners are relatively compact in size when compared to the rectangular cavity. Paper [9] shows design of cylindrical resonant TM$_{0m0}$ cavity with waveguide inputs.

We hence decide to implement circular TM$_{0m0}$ cavity resonator for power combining. The remaining challenge is to design the power combiner for microstrip line inputs. Our conceptual idea of microstrip-to- TM$_{0m0}$ cavity coupling is illustrated in Fig. 1. The microstrip line flares out at the cavity wall and gently couples the input TEM wave to the cavity azimuthal magnetic field. The width of the aperture opening of the flared microstrip line is nominally half-wavelength (in microstrip transmission line). The substrate is gradually tapered off to the center of the cavity to provide smooth transition to cavity mode.

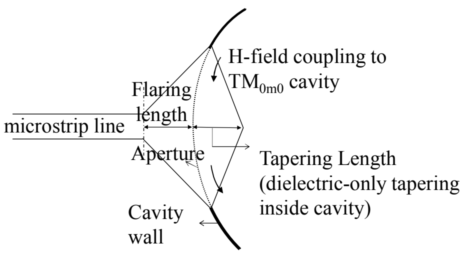


Fig. 1. Microstrip to TM$_{0m0}$ coupling

The next stage is the design of the coupling stage to the output TE$_{10}$ rectangular waveguide. In [9] the authors first couple the cavity TM$_{0m0}$ mode to cylindrical TM$_{01}$ mode in a circular waveguide. The circular waveguide is later coupled to the TE$_{10}$ rectangular output waveguide. The additional mode conversion stage makes the final power combiner less compact. Also vertical slits have to be cut on the circular waveguide to prevent undesired TE$_{11}$ mode from being excited in case of degradation of one or more power amplifier inputs. To avoid these problems, we decide to have a direct interface between the cavity and rectangular waveguide. The complete power combiner design is detailed in the following Section III. Fig. 2 shows a general view of the complete model of power combiner.

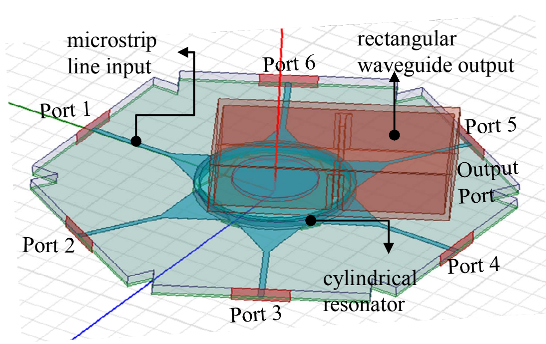
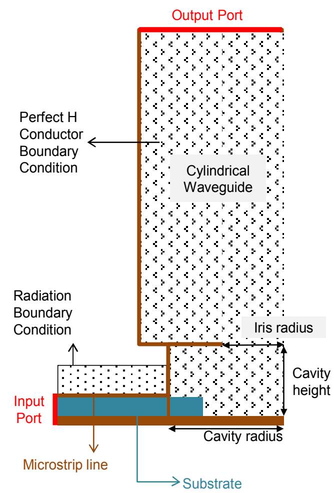


Fig. 2. General view of the power combiner (HFSS model)

III. Power Combiner Design

The design of the proposed cylindrical resonant cavity power combiner is divided into two stages. In the first stage we optimize a reduced model of the power combiner. Taking the optimized parameters from the reduced model, we later optimize the full model. ANSYS High Frequency Structure Simulator (HFSS) computational electromagnetic modeling software is used to simulate the structures and optimize the design parameters



Parameter	Value
Cavity, Cylinder thickness	1 mm
Conductor Material	Copper
Substrate	Rogers 6035 RTD
Substrate Height	0.508 mm
Microstrip Line Width	1.0767 mm
Microstrip Line Thickness	15.24 um
Cylinder Radius	14.8 mm

Fig. 3. Cross-sectional view of 1/6th model

A. 1/6th (reduced) model design

The purpose of simulating reduced model is to accelerate the design process. HFSS simulations are computationally intensive and having a reduced model helps to speed up the solver. Also a reduced model helps to work with fewer set of optimization variables in the preliminary stage.

Fig. 3 shows the structure of the reduced power combiner. We select TM$_{010}$ cylindrical cavity since this gives the smallest cavity size. Since we have 6 inputs, we break down the cavity in azimuthally symmetric fashion about its longitudinal axis into 6 sectors. The sectored-plane of the 1/6th cavity is set to perfect magnetic conductor boundary condition to support TM$_{010}$ mode. The reduced cavity is coupled to a reduced cylindrical waveguide to which we can attach a port. Note we cannot directly simulate coupling to output rectangular waveguide since the rectangular waveguide cannot be reduced in azimuthally symmetric fashion.

The reduced cavity is interfaced to flared microstrip input line with dielectric tapering. We use a commercial 50 ohm Rogers/Duriod 6035HTC (ε_r = 3.6) microstrip line since it features high thermal conductivity (1.44 W/K-m) [10] which is suitable for high power applications.

TABLE II
OPTIMIZATION VARIABLES FOR THE REDUCED MODEL

Parameter	Initial Value	Optimized Value
Aperture Width	$\lambda_{msl}/2 \;\; = 9.27$ mm	13.52 mm
Flaring Length	--X--	8.22 mm
Tapering Length	--X--	2.95 mm
Cavity Radius	11.89 mm (TM_{010} at 9.65 GHz)	13.95 mm
Iris Radius	--X--	8.00 mm
Cavity Height	$25.81\,mm < d < 43.45\,mm$ (or) $d < 22.69\,mm$ Mode Chart [11]	3.00 mm

Our optimization variables are detailed in Table 2 along with the initial values. We solve by adjusting the variable values about their initial values, and seeing the effect on the optimization criterion, which is to minimize reflection s-parameter of the input microstrip line port.

B. Full model design

In the full model design we simulate the complete structure with 6 microstrip line inputs and output rectangular waveguide. The optimization parameters are given in Table III.

We employ mode conversion from TM_{010} to TE_{10} by coupling the rectangular waveguide to the cavity iris. The coupling structure is given in Fig. 4.

The simulated insertion loss is less than 0.3 dB for 200 MHz bandwidth (Fig. 6). Return loss is < -20 dB (Fig. 5).

The rectangular waveguide breaks the symmetry of the radial power combiner structure. Transmission coefficients, return loss, graceful degradation (see Fig. 6) depends on the relative position of the input microstrip line to the rectangular waveguide (see Fig. 2, 4). To achieve uniform electrical characteristics, we vary slightly the flaring length pairwise for the input microstrip lines. The simulated return loss in case of 1 input amplifier failure is less than 12 dB (see Fig. 7).

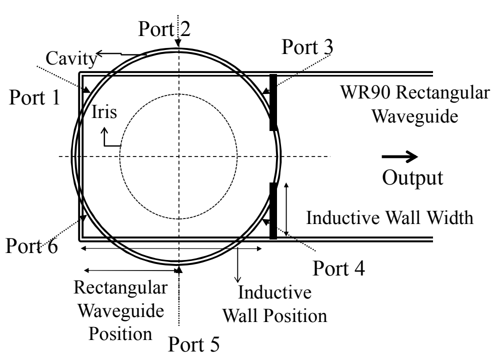


Fig. 4. Output Rectangular Waveguide Coupling

TABLE III
OPTIMIZATION VARIABLES FOR THE FULL MODEL

Parameter	Initial Value	Optimized Value
Rectangular WG Position	$\lambda_{rw}/4 = 10.59$ mm	10.1 mm
Inductive Wall Position	$\lambda_{rw}/2 = 21.18$ mm	20.99 mm
Inductive Wall width	--X--	3.70 mm
Aperture Width	From reduced Model	10.57 mm
Flaring Length	‘ ’	~12.54 mm
Tapering Length	‘ ’	2.45 mm
Cavity Radius	‘ ’	13.45 mm
Iris Radius	‘ ’	7.00 mm
Cavity Height	‘ ’	3.10 mm

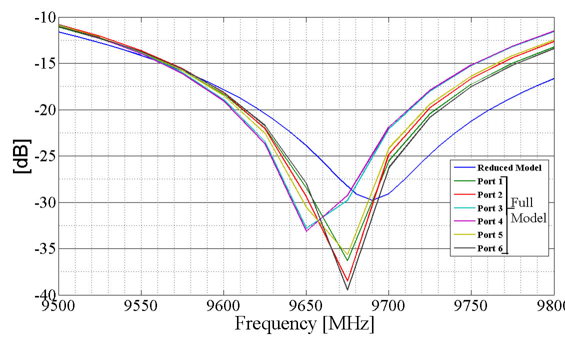


Fig. 5. Return Loss of reduced model and full model

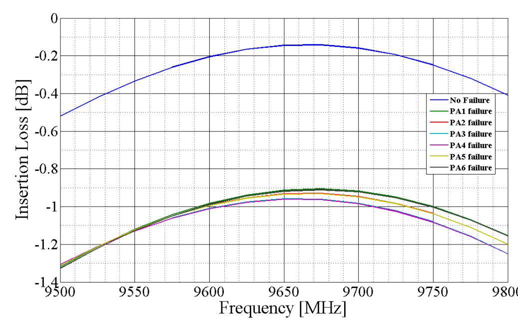


Fig. 6. Insertion Loss for the case of no failure and one input power amplifier failure

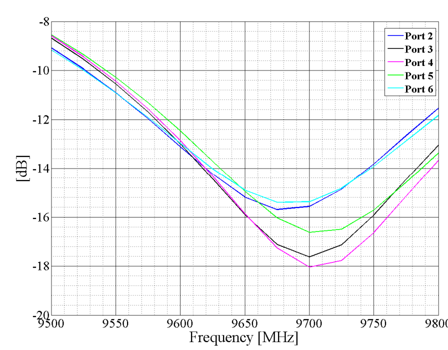


Fig. 7. Return Loss at the active input power amplifers, for the case of failure in input power amplifier #1

IV. CONCLUSION

In this paper we propose and design a cylindrical resonant cavity power combiner with microstrip input lines and rectangular waveguide output. The structure is very compact (combining cavity radius = 13.95 mm, height = 3.1 mm) and shows a low insertion loss of less than 0.3 dB over 200 MHz bandwidth at X-Band. Graceful degradation has been studied for 1 power amplifier failures. Return loss to the active input power amplifiers when there is one-input power amplifier failure is less than 12 dB.

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