Nuclear Inst. and Methods in Physics Research, A 905 (2018) 91–95

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

5-way radial power combiner at W-band by stacked waveguide micromachining

José R. Montejo-Garai [a,*], Jorge A. Ruiz-Cruz [b], Jesús M. Rebollar [a]

[a] *Grupo de Electromagnetismo Aplicado, Information Processing and Telecommunications Center, Universidad Politécnica de Madrid, Madrid, Spain*
[b] *Escuela Politécnica Superior, Universidad Autónoma de Madrid, Madrid, Spain*

ARTICLE INFO

Keywords:
Radial combiner
Transducer
Mode purity
N-way divider
Evanescent mode
Return loss
Isolation

ABSTRACT

This work presents a 5-way radial power combiner using the very low loss TE_{01} circular waveguide mode with a performance in the state of art for W-band. The accomplished design shows excellent characteristics: the experimental prototype has a return loss better than 20 dB, with a balance for the amplitudes of (±0.4 dB) and ($\pm 3.5^{o}$) for the phases, in a 12.8% fractional bandwidth (12 GHz centered at 94 GHz). In order to obtain these specifications, required for instance in plasma diagnosis systems or in power amplifiers, a meticulous step-by-step procedure is developed for both, the design and the challenging manufacture at W-band by stacked waveguide micromachining. The first step involves the design of a mode transducer, from the TE_{10} mode in the rectangular waveguide to the low-loss TE_{01} mode in the circular waveguide, with very high purity. In the second step, a 5-way radial power divider is designed. These designs, in order to be successful, have incorporated all the constrains for the manufacturing at W-band, using an E-plane stacked waveguide arrangement for low losses. The power combiner, made up by the transducer and the divider, has been manufactured with great accuracy using a very challenging assembly process, providing experimental results in very good agreement with the theoretical results.

1. Introduction

Development of systems at W-band requires high-power modules operating with high linearity and efficiency in a broadband, for use in industrial, research, defense, and space exploration areas. Weather radars, communication systems, air traffic control radar and some scientific facilities, such as particle accelerators or plasma diagnosis equipment, need also this power supply [1–3].

Traditionally, high power vacuum devices, such as magnetrons, klystrons, traveling wave tubes (TWTs), etc., have been used in pulsed or CW modes for the above exposed applications [4]. Nevertheless, they have some disadvantages compared to solid state technology such as high voltage power supply, limited filament lifetime, inherent thermionic noise, sensitivity to vibrations and cost. Thus, alternative schemes are becoming more popular for its progressive replacement. When a single solid-state power amplifier (SSPA) module is not able to supply enough power, merging several amplifiers to achieve the demanding power, by means of a combiner, is a suitable solution. The main challenge when designing this combiner is to achieve a low insertion loss in the combination process as well as a good balance in amplitude and phase for the signals in all output ports. A high return loss level in the input port and enough isolation between output ports are other important specifications to be considered.

Amongst the different type of combiners, those with radial symmetry exhibit a number of advantages over the corporate or chain-type combiners [5], mainly when a large number of ports are needed [6,7]. Because of the intrinsic symmetry of the arrangement, the power leaving the transducer travels equally in the radial direction to the output ports providing a theoretically perfect amplitude and phase division. Moreover, metallic waveguides are the preferred technology for high-frequency systems requiring high power capability, low insertion loss and rigid mechanical arrangement [8], features which are crucial for amplifier modules and plasma heating for fusion energy.

Different types of waveguide radial combiners can be found in the technical literature, mainly in Ku and Ka bands [8–12]. However, in W-band, the radial symmetry is not usual in power combiners. A four-way corporative waveguide power divider implemented in H-plane configuration with the T-junction as divider element is presented in [13], with a theoretical return loss (the measurement is carried out in back-to-back configuration) higher than 10 dB in a 11.8% relative bandwidth (96–108 GHz). In [14] a four-way waveguide power divider is shown with a return loss higher than 13 dB in a 31.6% relative bandwidth

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[*] Corresponding author.
E-mail address: jr@etc.upm.es (J.R. Montejo-Garai).

https://doi.org/10.1016/j.nima.2018.07.031
Received 28 May 2018; Received in revised form 6 July 2018; Accepted 11 July 2018

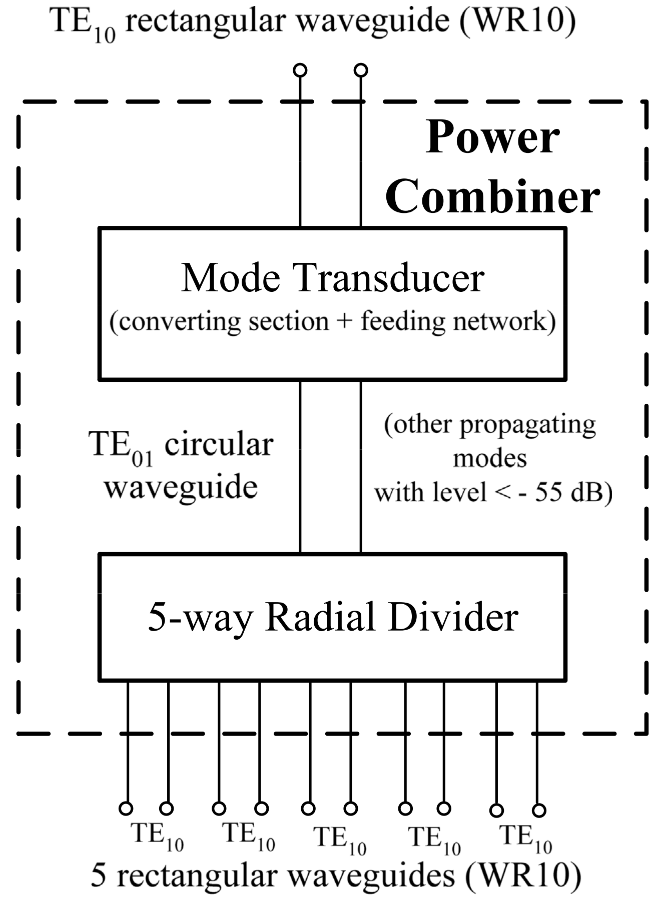

Fig. 1. Scheme of the power combiner composed of the mode transducer between the rectangular mode TE_{10} and the circular mode TE_{01}, and the 5-way radial divider.
Source: Adapted from Fig. 1 in [8].

(80–110 GHz), but the drawback of output ports with 180° out of phase.

Nevertheless, a W-band solid-state power amplifier based on two different kinds of waveguide combiners: a 4-way septum waveguide combiner and a 12-way radial-line waveguide combiner, is presented in [3]. The 4-way septum waveguide combiner is a corporate structure 1:4 [5]. On the other hand, the 12 way radial-line waveguide combiner is formed by a transition from WR-10 waveguide to coaxial and then into the central radial-line section. In this way, the signal expands outward radially, and then, a new transition to WR-10 is implemented. This structure is highly different from that proposed in our work, where a sidewall coupling is used to connect every WR-10 to the circular waveguide.

Therefore, the goal of this work is to design a compact W-band five-way radial power combiner with high performance, giving priority to the following key requirements: the return loss level, the insertion loss, the power handling and the amplitude–phase balance (Fig. 1). Additionally, there is a key point in the excitation and symmetry of the transducer from rectangular to circular waveguide that feeds the divider, which is closely related to the control of the propagating modes with cut-off frequencies below and above the TE_{01} circular mode in the operation band, in order to obtain a suitable amplitude–phase balance in the output ports. Fig. 1 shows a detailed scheme of the power combiner composed of the mode transducer between the rectangular mode TE_{10} and the circular mode TE_{01}, and the 5-way radial divider (scheme adapted from Fig. 1 in [8]). In this design, the other propagating modes in the 88 to 100 GHz band are excited with a level 55 dB lower than the desired mode TE_{01}.

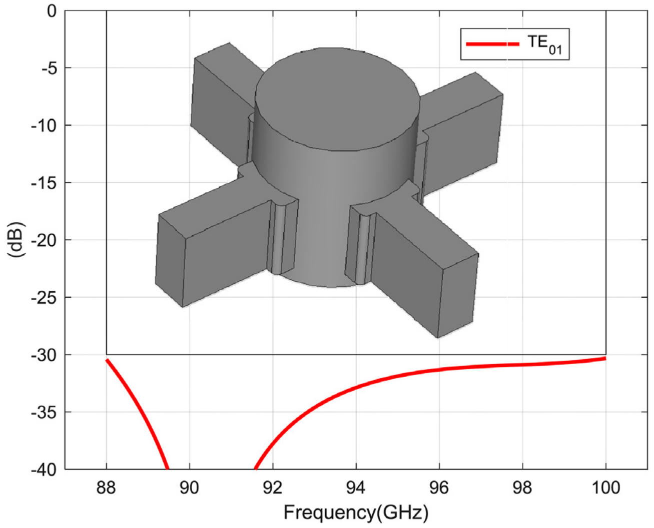

Fig. 2. Simulated response of the converting-section: reflection coefficient of the TE_{01} mode. In the inset, a 3D CAD view of the device is shown.

2. Design of the TE_{01} mode transducer

The TE_{01} circular mode transducer is an essential device in several areas of radiofrequency engineering, not just integrated in a power combiner, but as an independent component for use in other applications. It is of great interest in long transmission systems since the attenuation constant of the TE_{01} mode, due to finite conductivity walls, is gradually smaller as the frequency increases [15]. Likewise, it is used in the design of very high-Q resonant cavities for application in fields like gyrotrons, plasma-heating systems, and high-energy environments [16–18]. Moreover, and directly related to this work, radial power combiners have extensively used this kind of transducer for long time [10].

The mode transducer uses a sidewall coupling between the rectangular and the circular waveguides [19,20] as physical procedure to transfer the electromagnetic energy between them. Before any other consideration, it must be taken into account that the TE_{01} mode is not the dominant mode of the circular waveguide. That is the reason to analyze the propagating modes considering the number of symmetry planes of the physical structure, the excitation (rectangular waveguide TE_{10} mode) and the desired circular waveguide TE_{01}mode. An exhaustive study of this question can be found in [8], where the geometry developed there has been the starting point to the design of the transducer in W-band.

The sidewall coupling transducer consist of the converting-section and the input feeding network (Fig. 1). Therefore, the first task has been the design of the converting-section having in mind the limitations of the micromachining process, considering a rounded corner of radius 0.2 mm and forcing to maintain the width of the four WR10 waveguide when connected to the circular waveguide with a stepped transformer, always to ease the fabrication. Besides, a circular post has also been placed on the circular bottom to enhance both, the bandwidth and the return loss. Fig. 2 shows the simulated response of the converting-section, obtained with (CST) [21].

The second task is to feed the converting-section from the input rectangular port, maintaining the symmetry plane when exciting the four ports. Besides, it is necessary to preserve the bandwidth and the return loss level obtained previously in the converting-section.

The feeding-network is composed of two types of T-junctions and three kinds of waveguide bends, all in E-plane configuration, setting one symmetry plane for the whole structure (see the inset in Fig. 3). A step-by-step process has been carried out in the design of all these individual components separately before a final optimization of the