A New 3-dB Power Divider for Millimeter-Wavelengths

Vessen Vassilev, Victor Belitsky, *Member, IEEE*, Denis Urbain, and Sergey Kovtonyuk

***Abstract*—This paper presents a new type of 3-dB power divider that achieves wide-band, low-loss, and symmetric power division. In the paper, we discuss the design considerations and present results of measurements at 10 and 100 GHz. The power divider symmetry is examined as a function of the termination loads mismatch. The simplicity of the presented divider makes it very suitable for application at millimeter and submillimeter bands. The predicted and the measured performance are in very good agreement.**

***Index Terms*—Millimeter-wave, power divider, side band separation receiver, waveguide-to-microstrip transition.**

I. Introduction

Branch-type 90° couplers and 180° hybrids are usual elements of balanced or sideband separating receivers at microwave frequencies. Recently, this receiver technology shifts up in frequency approaching the millimeter-wave band [1]–[3]. At these frequencies, a rectangular waveguide provides the lowest loss and is frequently used as an input for the receiver. Low insertion loss, symmetric power division, and phase balance are requirements [1] for power divider to be used at both RF and local oscillator channels. Most of the existing power-dividing schemes used for microwave applications are relatively difficult to implement for the millimeter-wave band, e.g., around 300 GHz. Power splitting can be provided in the waveguide using, e.g., magic T [4], over a relatively narrow frequency band. Waveguide branch-type couplers appear to be very suitable and recently reported to be fabricated for up to 700 GHz [5] but still might be challenging for machining. In order to provide the required amplitude symmetry over the entire band, several branch sections have to be cascaded necessitating longer waveguide lines and correspondingly more insertion loss. An attractive solution is suggested in [2], [3] using a branch-line coupler and Wilkinson power divider based on a planar line structure. This requires a planar terminating and balancing resistors that, with necessary tolerances, might be difficult component for a thin-film processing.

We suggest a power divider where a double probe structure is coupled to the E-field in a waveguide; the probes split the input RF signal with minimum loss over a wide frequency band and simultaneously provide transition from waveguide to microstrip line for easy integration with the subsequent receiver frontend (mixer) circuitry.

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V. Vassilev, V. Belitsky, and D. Urbain are with the Radio and Space Science Department, Chalmers University of Technology, Gothenburg, Sweden (e-mail: vevas@oso.chalmers.se).

S. Kovtonyuk is with the Institute of Radio Engineering and Electronics, Moscow, Russia.

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II. Design Considerations

The waveguide to microstrip power divider is shown in Fig. 1. The input port 1 is a waveguide and the output ports 2 and 3 are microstrip lines patterned on a substrate located $\lambda/4$ from the waveguide backshort. The substrate is crystal quarts placed in a channel with subcritical dimensions to prevent propagation of waveguide modes in the substrate channel. The E-field for the dominant mode has its maximum at the center of the substrate at equidistant point from the probes. The E-vector oscillates in the direction that is parallel to the probes orientation inducing antisymmetrical currents. The probes 5, placed in the middle of the broad wall of the waveguide, are followed by high impedance microstrip lines 6, which transform the capacitive component of the probes impedance. Tapered lines provide the transition between the high impedance lines to the 50 Ω output lines 7.

A fundamental property of a lossless reciprocal three-port device is that all three ports *cannot* be simultaneously matched unless a resistor is introduced to compensate the coupling between the output ports, as in the Wilkinson power divider. In our design, we avoid the use of resistor allowing coupling between the output ports, i.e., $S_{23} \neq 0$. To evaluate the tradeoff between the output ports reflection S_{22}, S_{33}, and output port coupling S_{23} we set our priority to be the loss less symmetrical power division having input reflection $S_{11} = 0$ and $|S_{21}| = |S_{12}| = |S_{31}| = |S_{13}| = \sqrt{2}/2$ with scattering matrix

$$\begin{vmatrix} |S_{11}| & |S_{12}| & |S_{13}| \\ |S_{21}| & |S_{22}| & |S_{23}| \\ |S_{31}| & |S_{32}| & |S_{33}| \end{vmatrix} = \begin{vmatrix} 0 & \sqrt{2}/2 & \sqrt{2}/2 \\ \sqrt{2}/2 & |S_{22}| & |S_{23}| \\ \sqrt{2}/2 & |S_{32}| & |S_{33}| \end{vmatrix}$$

Applying the energy conservation condition for the second column in the S matrix gives us $|S_{22}|^2 + |S_{32}|^2 + 0.5 = 1$. A reasonable tradeoff would be

$$|S_{22}| = |S_{33}| = |S_{32}| = |S_{23}| = -6 \text{ dB}. \quad (1)$$

Critical parameters in achieving the required tradeoff from (1) over as wideband as possible are the spacing between the two probes and the probes' shape. These parameters were optimized using High Frequency Structure Simulator [7], and the device geometry was found. To ease the phase measurement a scale model was built at 8.5–12.5 GHz and measured with a vector network analyzer. The measured impedance at the output ports is shown in Fig. 2. The distance between the probes and the interaction between the probes and the following inductive lines

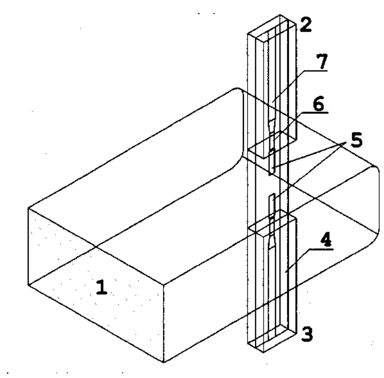

Fig. 1. Waveguide to microstrip power divider. 1—the input port, 2, 3—the output ports, 4—channel with the substrate, 5—probes, 6—high impedance line, 7—output microstrip line.

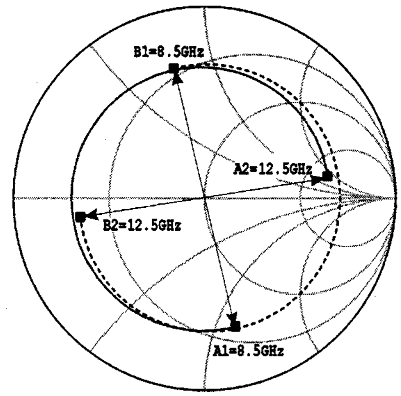

Fig. 3. Measured input–output complex transmission S_{21}, S_{31}.

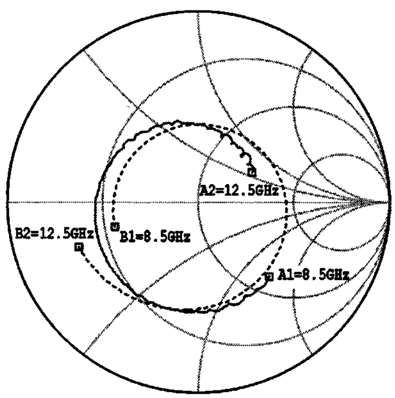

Fig. 2. Measured coupling between the output ports S_{32} (trace A) and the measured output impedance S_{22}, S_{33} (trace B).

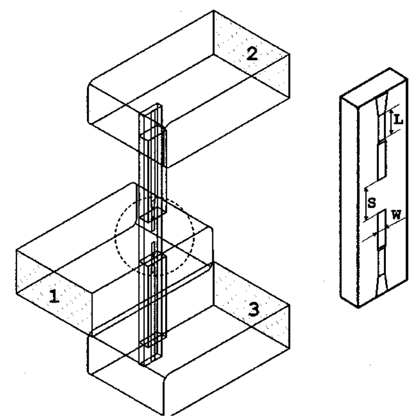

Fig. 4. Waveguide to microstrip power divider as it was measured at 100 GHz. The microstrip ports were replaced with microstrip to waveguide transitions. The waveguide is WG-10, the structure dimensions are $S = 340$ μm, $W = 95$ μm, $L = 270$ μm, and the substrate cross section is 610/150 μm.

provide impedance curve such that its center coincides with the center of the Smith diagram and thus constant $|\Gamma| \approx -6$ dB is provided for all frequencies in the band (Trace B). Similarly, the coupling (Trace A) is also a circle centered in the middle of the Smith chart providing constant magnitude of $S_{23} \approx -6$ dB in the pass band. Thus the performance of the power divider becomes independent on the spacing between the output ports (the length of the transmission line 7).

III. Measured Performance

The device was fabricated on a crystal quartz substrate ($\varepsilon_r = 4.44$) using standard photolithography process and DC magnetron spattered gold layer. In order to reduce the source and loads match error terms at 10 GHz measurements, a complete two-port calibration was performed at the SMA ports of the analyzer while the measurements were performed using a "direct" method [6] where two of the ports were accessed at a time, while the third was match terminated. A high-quality SMA-to-waveguide transition was used to provide waveguide source to feed the structure and its loss is taken into account in the measurements. The measured transmission between the input and the output ports S_{21}, S_{31} is shown in Fig. 3

Both responses resemble a circle at the center of the Smith chart having radius 0.707 providing constant transmission of ≈ -3 dB. This power divider is a perfect 180° frequency independent phase shifter and is very much suitable for balanced mixer application. The phase difference at the output ports remains constant even if the structure is terminated with asymmetric loads. Fig. 3 shows two pairs of points taken at the beginning and at the end of the band for both S_{21} and S_{31}, the lines connecting this points cross the Smith chart in the center.

In order to confirm the predicted performance at millimeter-waves a power divider has been built and measured at 85–115 GHz using a multi-channel scalar network analyzer.

To facilitate measurements with waveguide adapters at millimeter wavelengths, additional microstrip to waveguide transitions were designed and connected at the microstrip ports, Fig. 4. The transmission S_{21} and S_{31} was measured between 85 and 115 GHz and is plotted in Fig. 5, the typical total loss is $\approx$0.3 dB over 30% of bandwidth and include losses in the microstrip to waveguide transition. In this measurement only response calibration was performed and this results in ripples caused by the interaction between the system's source and loads mismatch. Since the output ports are coupled, the amplitude asymmetry is likely caused by possible difference in the load terminations.

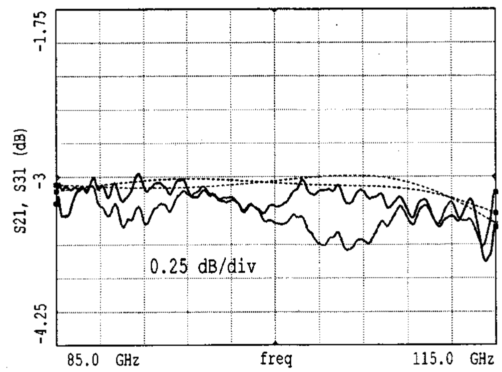

Fig. 5. Measured transmission magnitude of the power divider at 100 GHz (solid lines) and the simulated transmission (dashed lines).

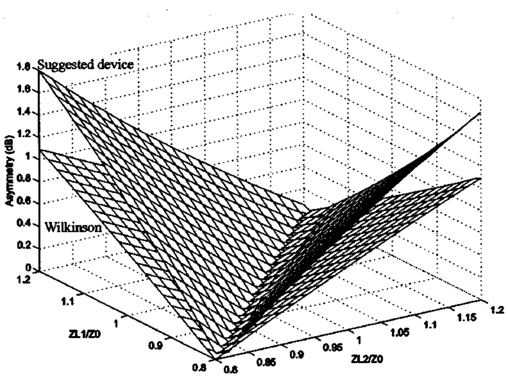

Fig. 6. Asymmetry in the power delivered to the loads as a function of the load impedance deviation from the optimum value Z_0. The upper surface represents the asymmetry produced at the suggested divider; the lower surface characterizes the corresponding asymmetry in the ideal Wilkinson power divider.

IV. Effect of the Output Ports' Termination

Unlike the ideal Wilkinson power divider, if a reflected wave is generated at one of the outputs of the structure, it gets distributed between the input and the other output of the circuit. As result, the -3 dB power division symmetry turns out to be more "sensitive" to the load deviation from its nominal value. The power divider transducer power gain (TPG) was examined for different values of the loads mismatch.

The asymmetry, which is the difference in the TPG between the two channels, is plotted in Fig. 6 and compared to the asymmetry, which would be observed in the ideal Wilkinson-type power divider. From the plot it can be noticed that for small impedance deviations Z_L/Z_0 the asymmetry of the power divider converges to one of the ideal Wilkinson divider. Fig. 6 shows that even with mismatch at the outputs, as long as $Z_{L1}/Z_0 = Z_{L2}/Z_0$, the suggested device continues to provide symmetric power division as with the Wilkinson divider.

V. Conclusion

We present power divider based on a double-probe structure coupled to a waveguide. The device has been modeled and optimized using HFFS electromagnetic simulation package. We have achieved a very good agreement between the simulated and the measured performance with typical measured insertion loss of 0.2–0.3 dB at 85–115GHz and nearly negligible amplitude imbalance of ≈0.3 dB. Our measurements confirm that the suggested power divider provides extremely low insertion loss and broadband operation limited only by the dominant mode in the waveguide. The power divider is a perfect phase-splitter, since the E-field vector oscillates in the direction parallel to the probes; phase difference of 180° is introduced between the output ports for all frequencies of the waveguide dominant mode. The device is fabricated using microelectronics processing technique that allows accurate patterning convenient to scale for millimeter and submillimeter wavelengths and it can be used in balanced or sideband separation receivers at these wavelengths.

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