Experiments of Device Failures in a Planar Nine-Way Metamaterial Power-Combined Amplifier

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Abstract

The degradation characteristic of a planar nine-way metamaterial power-combined amplifier with device failures is investigated in this paper. The power-divider/combiner design is based on the metamaterial lens structure and is composed of positive refractive index material and zero refractive index (ZRI) material. Nine 1-W power amplifiers are inserted in the ZRI material to attain a nine-way power-combined amplifier. Due to its uniform isolation characteristics of the metamaterial power divider/combiner, the graceful degradation performance of this power-combined amplifier is shown to be independent of the amplifier failure sequence and is experimentally demonstrated.

1. Introduction

Due to the power capacity of solid-state devices, power combining of multiple devices becomes necessary as a higher output power level is required. Therefore, development of microwave power-dividing/combining techniques [1] of solid-state devices to achieve low loss and high combining efficiency is desirable. Besides the higher power generation, the graceful degradation performance of the associated solid-state devices is also an important issue in developing the power-dividing/combining techniques [2]. Specifically, as one or more of active solid-state devices fail, the power-combined amplifier should still be operable. As the number of active devices increases, *N*-way power-dividing/combining structures, such as Wilkinson [3] and radial [4] structures in a parallel configuration, are usually used due to compactness. These structures do not have the disadvantage of increasing loss with the number of active devices existed in chain and tree configurations. However, their main problem is having noncollinearly aligned multiple ports to make their integration with active devices in a planar structure difficult.

Recently, metamaterials with negative refractive index having left-handed (LH) propagation behavior are extensively applied to microwave devices [5]. Specifically, they are composed of one-dimensional or two-dimensional (2-D) right-handed (RH) and LH transmission lines called composite right/left-handed (CRLH) transmission lines [6]. By properly operating CRLH transmission lines at the infinite wavelength frequency, metamaterials can have a zero-phase shift characteristic along the structure to give an equal magnitude and phase distribution [7]. Based on this characteristic, planar [8, 9] metamaterial power dividers using positive refractive index (PRI) material and zero refractive index (ZRI) material are presented. Specifically, the PRI material is composed of 2-D RH unit cells, while the ZRI material is realized by arranging 2-D RH and LH unit cells in a checkerboard tessellation [8], or by using only LH unit cells operated at the infinite wavelength frequency to give the zero-phase shift characteristic [9].

This paper investigates the degradation characteristic of a planar nine-way metamaterial power-combined amplifier [10] with device failures. Due to its uniform isolation characteristics of the metamaterial power-dividing/combining structure [9], the graceful degradation performance of this power-combined amplifier is shown to be independent of the amplifier failure sequence. It is then different from that of using radial power dividers and combiners with isolation resistors [4].

2. Design

Fig. 1(a) shows the schematic of a planar nine-way metamaterial power-combined amplifier. The divider and combiner structures are composed of RH unit cells for PRI material and LH unit cells for ZRI material with their structures of RH and LH unit cells shown in Fig. 1(b) and (c). The semi-circular interface between PRI and ZRI materials is approximated in a staircase manner. Each of the power divider and combiner includes 9 × 7 cells. Ports 1 and 2 located at the central RH unit cells of two PRI materials are the input and output ports, respectively. The remaining ports which are not indexed are open circuits. Nine amplifiers are directly connected to the divider output ports and the combiner input ports.

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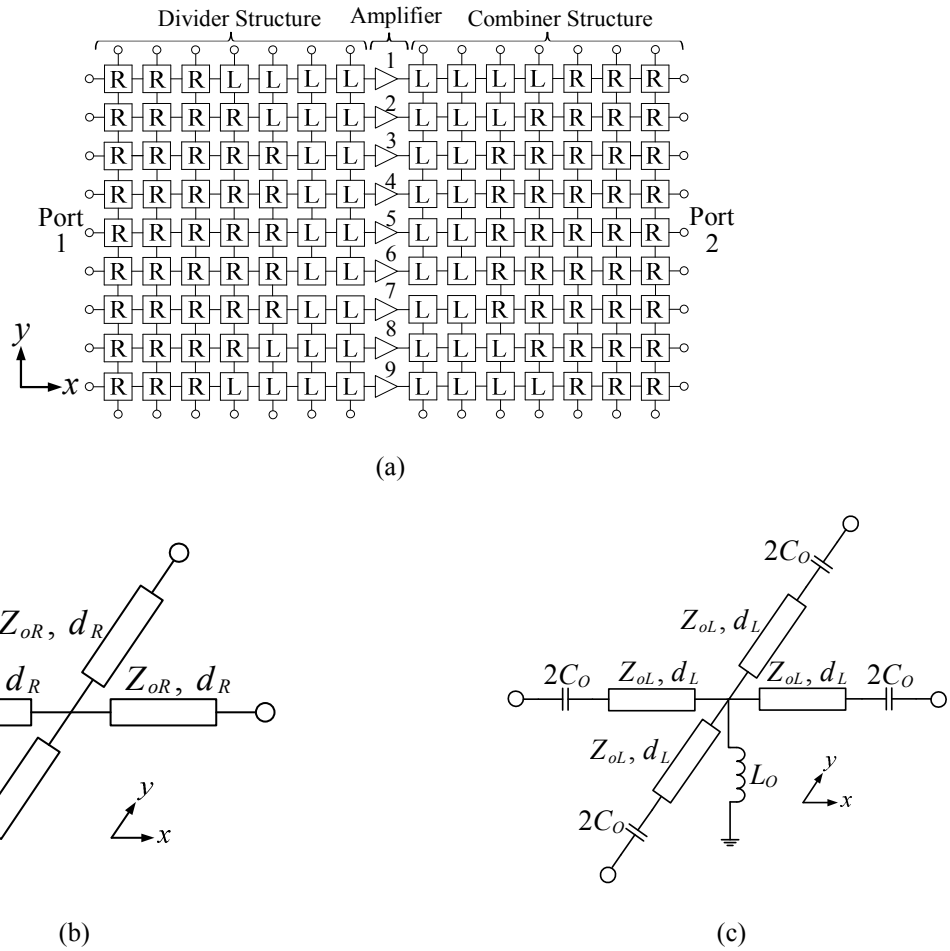


Fig. 1. (a) Schematic of a planar nine-way power-combined amplifier with *R* representing (b) RH unit cell and *L* representing (c) LH unit cell.

2.1 Divider and Combiner

A nine-way power divider/combiner is designed on a 1.575-mm-thick RT/Duroid 5880 substrate with $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$. The operating frequency is 1 GHz. The size of RH and LH unit cells is given by 10 mm × 10 mm, and the characteristic impedance $Z_{oR} = Z_{oL} = 100\ \Omega$. The length $2d_L$ of LH unit cell is 8 mm by considering the size of 0402 surface-mounted capacitor.

2.2 Amplifier

The amplifiers used to implement this nine-way power-combined amplifier are Hittite HMC452ST89E GaAs InGaP HBT 1-W amplifiers. Fig. 2 shows the circuit schematic of an 1-W amplifier. The termination impedances are 10 Ω which is obtained by calculating the input impedances at the divider output ports and the combiner input ports. The *S*-parameters, which are given for 1-W output power of this HBT amplifier, are then used to design the input and output conjugate matching circuits as shown in Fig. 2.

3. Experimental Results

The nine-way power-combined amplifier circuit is shown in Fig. 3. MuRata 0603 36-nH SMD inductors and 0402 5.6-pF SMD capacitors are used in the realization of the LH unit cell. The shunt inductor L_O of the LH unit cell is placed upright in a hole drilled through the substrate.

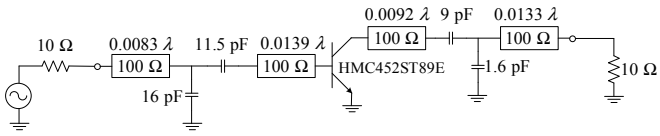


Fig. 2. Circuit schematic of an 1-W amplifier.

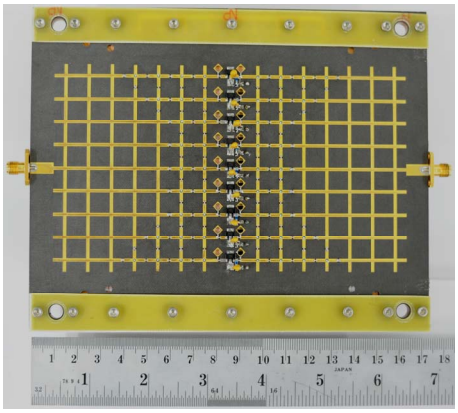


Fig. 3. Photograph of a planar nine-way power-combined amplifier circuit.

For a single amplifier, the measured output power at 1-dB gain compression point is 30 dBm. Fig. 4(a) shows the measured results of output power, power gain, and PAE of the nine-way power-combined amplifier at 1.008 GHz. The output power of 38.83 dBm at 1-dB gain compression point is obtained as the input power is 26.83 dBm, and the corresponding DC bias voltage and current are 5 V and 3.586 A to give a PAE about 40%. The power-combining efficiency is then 85%.

Three sequences of failed amplifiers are used to demonstrate the graceful degradation characteristic of this power-combined amplifier, as shown in Fig. 4(b). The failed amplifiers in each sequence are emulated by turning off the biases of corresponding operating amplifiers. The numbering and position of nine amplifiers can be observed from Fig. 1(a) and Fig. 3. In the first and second sequences, one, two, three, four, and five amplifiers are turned off successively in an ordered manner and they are represented by (9, 5, 1, 3, 7) and (5, 4, 6, 3, 7), respectively. In the third sequence, two and four amplifiers are turned off successively and are represented by (1, 9, 2, 8). The ideal degradation characteristic of an *N*-way power-combined amplifier with *N* amplifiers being reasonably matched and having adequate isolation is given by [2]

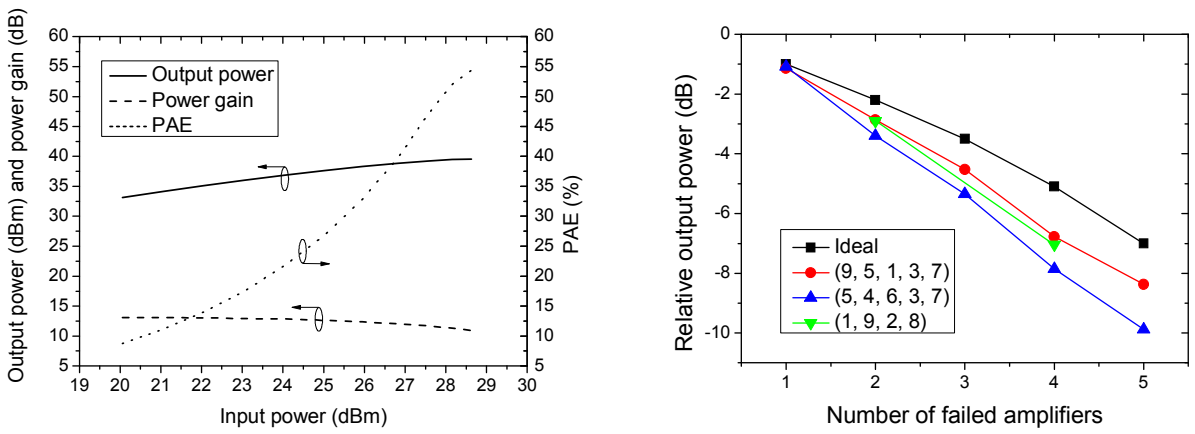
$$\frac{P_{out}}{P_{out,max}} = (1-\frac{m}{N})^2 \tag{1}$$

where P_{out} is the output power as *m* amplifiers fail and $P_{out,max}$ is the maximum output power as there is no amplifier failure. As shown in Fig. 4(b), compared to ideal results of (1), an additional power drop in each sequence is observed and shown increasingly as the number of failed amplifiers increases. It results from source and load mismatches of the remaining operating amplifiers. Note, the amplifiers are matched only as nine identical excitations are at the input ports of combiner for the termination impedances of 10 Ω. It is then different from that of using radial [4] power dividers and combiners which have isolation resistors to retain matched inputs and outputs for the remaining operating amplifiers.

In addition, as shown in Fig. 4(b), due to port-independent isolation characteristics for both power divider and combiner, similar graceful degradation characteristics for these three sequences of failed amplifiers are observed. A slightly better performance for the first and third sequences than that of the second sequence may be due to nonuniformity of nine amplifiers. Note, the results given in Fig. 4(b) are different from those observed in [4] which are dependent on the specific sequence of failed amplifiers due to port-dependent isolation characteristics of radial power-dividing/combining structures.

4. Conclusion

Device failures in a planar power-combined amplifier using the metamaterial power-dividing/combining structure are studied experimentally in this paper. Due to its uniform isolation characteristics of the metamaterial power divider/combiner, the graceful degradation characteristic of this nine-way power-combined amplifier is shown to be independent of the amplifier failure sequence and different from that of using radial power divider and combiner.



(a) (b)

Fig. 4. Measured results of (a) the output power, power gain, and PAE and (b) the output power degradation at 1.008 GHz.

5. Acknowledgments

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