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A 6-port coupler has been implemented for use in an RN2 beam former at 60 GHz. The coupler was synthesized to provide the appropriate magnitude and phase division and then realized using micro-machined TEM transmission lines. At 60 GHz, all signal paths of the coupler have a measured insertion loss less than 1.14 dB and a phase error of less than 3.8 degrees.

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A 6-port 60 GHz coupler for an RN^2 beam former

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Abstract

A 6-port coupler has been implemented for use in an RN^2 beam former at 60 GHz. The coupler was synthesized to provide the appropriate magnitude and phase division and then realized using micromachined TEM transmission lines. At 60 GHz, all signal paths of the coupler have a measured insertion loss less than 1.14 dB and a phase error of less than 3.8 degrees.

1 Introduction

The RN^2 family of beam formers was originally presented by McFarland [1,2]. This family of beam formers is interesting because it allows the realization of a two-dimensional beam forming matrix that maps to a two-dimensional array arranged in a triangular lattice. The general concept is similar to the well known Butler matrix, and in fact, a Butler matrix is an RN^2 matrix where $R = 1$ and $N = 2^k$ for any integer k. The RN^2 family allows two dimensional beam forming matrices to be designed without cascading one-dimensional Butler matricies. However, implementation of RN^2 matrices can require the use of non-standard components whereas Butler matrices rely only on 4-port quadrature hybrid couplers. In this work, we present a 6-port coupler designed for application in an $R = 3$, $N = 3$, RN^2 beam forming matrix at 60 GHz. A literature search did not yield any previous implementation of a 6-port coupler with the desired power and phase split, and therefore, the coupler was synthesized using the techniques detailed by Jiménez [3]. The resulting design was then fabricated using three dimensional micromachining to form rectangular coaxial (recta-coax) lines [4]. At 60 GHz, all signal paths of the coupler have a measured insertion loss less than 1.14 dB and a phase error of less than 3.8 degrees. Over a 600 MHz (1%) bandwidth, the maximum insertion loss and phase error are less than 1.24 dB and 6.9 degrees respectively.

2 Design

An RN^2 beam former matrix with $R = 3$ and $N = 3$ requires the design a single six-port coupler. The power and phase split of this matrix was detailed by Chadwick [2]. The desired S-parameters of a six-port implementation of this matrix are

$$S_{coup} = \sqrt{\frac{1}{3}} \begin{bmatrix} 0 & 0 & 0 & e^{-j\phi_1} & e^{-j\phi_1} & e^{-j\phi_1} \\ 0 & 0 & 0 & e^{-j\phi_1} & e^{-j\phi_2} & e^{-j\phi_3} \\ 0 & 0 & 0 & e^{-j\phi_1} & e^{-j\phi_3} & e^{-j\phi_2} \\ e^{-j\phi_1} & e^{-j\phi_1} & e^{-j\phi_1} & 0 & 0 & 0 \\ e^{-j\phi_1} & e^{-j\phi_2} & e^{-j\phi_3} & 0 & 0 & 0 \\ e^{-j\phi_1} & e^{-j\phi_3} & e^{-j\phi_2} & 0 & 0 & 0 \end{bmatrix}, \qquad (1)$$

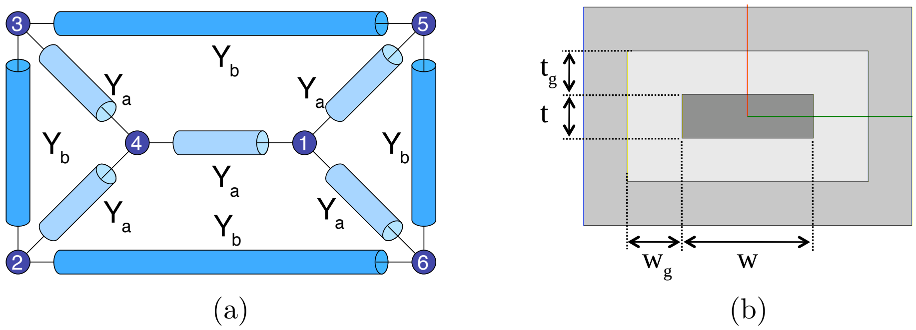


Figure 1: (a) Synthesized distributed-element network for the 6-port coupler. (b) Cross section of the recta-coax line.

Table 1: Line parameters and dimensions.

Line	Z_0	Length (deg.)	Length (mm)	w (mm)	w_g (mm)	t (mm)	t_g (mm)
Y_a	50	60	0.833	0.100	0.065	0.043	0.05
Y_b	43.29	270	3.75	0.130	0.065	0.043	0.05

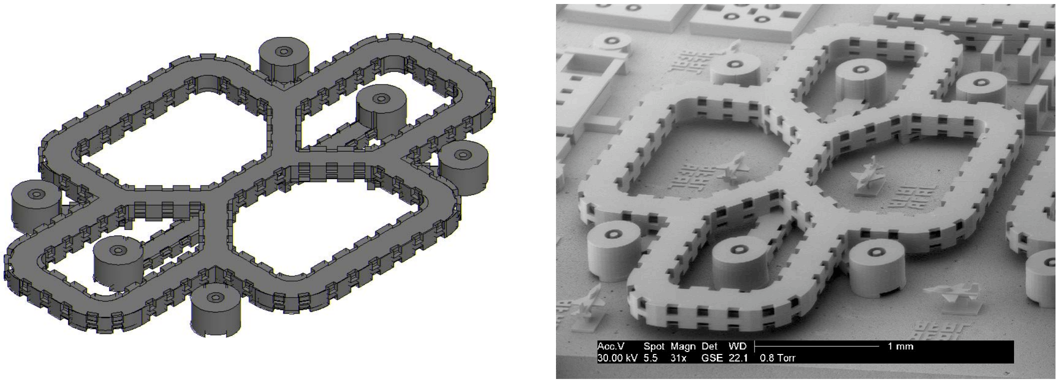
where ϕ_1 is the reference phase, $\phi_2 = \phi_1 + 120$ deg, and $\phi_3 = \phi_1 - 120$ deg. Following the procedure of Jiménez [3], a distributed-element network was synthesized. The resulting network layout is shown in Fig. 1 and the line parameters are provided in Table I. The network is relatively simple, but a two dimensional layout requires interior ports. Therefore, a physical implementation of the network can only be done in technologies that support multiple layers of transmission lines. For this work, layout was done using recta-coax lines. The network from Fig. 1 was translated into recta-coax lines, and a finite element model was created. Several iterations of the design were performed to optimize the line lengths and junctions resulting in the final layout shown in Fig. 2 (a). The final line lengths and cross sectional dimensions are provided in Table I. The cross sectional dimensions of the line are labeled in Fig. 1 (b).

3 Fabrication

The coupler was fabricated using a commercial process called EFAB [5]. Under contract, designs were submitted to Microfabrica, Inc. and the couplers were fabricated in nickel. Two couplers were fabricated on each die site. Multiple die sites were fabricated and returned to the authors for testing. Fig. 2 (b) shows a scanning electron microscope picture of the fabricated coupler.

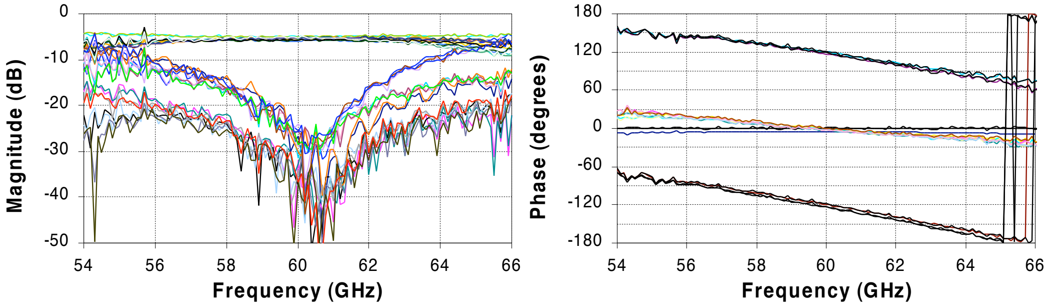
4 Measurements

The S-parameters of the six-port coupler were obtained by applying the renormalization technique reported by Tippet and Speciale [6]. The technique requires a set of two-port measurements of the coupler, which were taken on an Agilent E8361A vector network analyzer (VNA). A Thru-Reflect-Line (TRL) VNA calibration was



(a) (b)

Figure 2: (a) A three dimensional finite element model, and (b) a scanning electron microscope picture of the final coupler design.

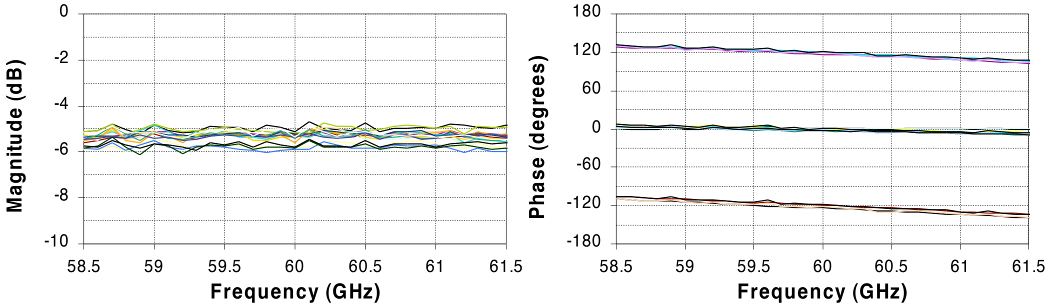


(a) (b)

Figure 3: Measured scattering parameters of the 6-port coupler.

performed over the frequency range of 30 GHz to 67 GHz using standards fabricated on-wafer with the coupler. The standards consist of a 0.4 mm line, a 0.2 mm shorted line, and a 1.0 mm line. The recta-coax lines have 50 Ω impedance and transition to 50 Ω circular coaxial lines. The circular coaxial lines are normal to the substrate and can be probed from any direction to facilitate measurements. Identical transitions are used on the coupler and are visible in Fig. 2. The renormalization technique requires measurements of all combinations of the six ports taken two at a time, a total of fifteen unique two-port measurements. For each measurement, the other four ports were left open. Since a TRL calibration is used, each two-port measurement represents the six-port coupler with four of its ports terminated in the recta-to-circular coax transitions. A one-port measurement of the 0.4 mm TRL line provides the measured termination for renormalization.

Fig. 3 shows the renormalized scattering parameters over a 20% bandwidth. As can be seen, the measured coupling is very good over this entire range. However, the linear phase versus frequency shown in Fig. 3 (b) limits the bandwidth over which the coupler can be used in a beam former. Fig. 4 shows the measured coupler performance over a 5% bandwidth. The magnitude plot is shown for only the coupled, and not the isolated lines. The ideal (1/3) power split would result in a magnitude of −4.77 dB.



(a) (b)

Figure 4: Measured scattering parameters of the 6-port coupler.

5 Conclusion

A 6-port coupler for use in a RN^2 beam former has been synthesized and fabricated. The realized coupler performs exactly as designed. The coupler has been successfully realized in a single design pass. Utilizing this coupler, a beam-forming matrix for a 27 beam array would be expected to have an insertion loss of approximately 5-6 dB.

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