A High-Temperature Superconducting Butler Matrix

Alonso Corona, *Member, IEEE*, and M. J. Lancaster, *Member, IEEE*

***Abstract*—This paper presents a novel configuration of a beamforming 16-port Butler matrix centered on a frequency of 2 GHz. The structure is implemented using high-temperature superconductors (HTS).**

In communication and remote sensing systems, multibeam antenna systems are gradually replacing single-beam systems. Microwave beamformer circuits for these applications require a large number of couplers and phase shifters, which result in a large circuit size. By using microstrip structures on high permittivity substrates, the circuits can be miniaturized. However, the insertion loss of the beamformer increases due to the conductor loss. The use of HTS allows reduction in the size of the circuit while maintaining low insertion loss, due to the low conductor loss compared to conventional conductors.

The Butler matrix described here uses a two-layer configuration, which removes any microstrip line crossovers; it can be constructed by traditional photolithographic methods.

In this paper, the design of the matrix is discussed, together with the experimental and simulated results.

***Index Terms*—Beam scanning, beamformers, Butler matrix, high-temperature superconductors (HTSs), intelligent antenna systems, space-division-multiplexing access (SDMA), spatial discriminator, superconducting applications.**

I. Introduction

THERE HAS been a broad range of research covering development of antenna arrays with beamforming capabilities for mobile communications. As systems require more channel capacity, it is anticipated that steerable antennas consisting of many radiating elements fed by beam-forming networks will be incorporated in future generations of mobile communications systems.

So far, mobile communication systems have used three main types of multiple access schemes: frequency-division multiple-access, time-division multiple-access, and code-division multiple-access. Another scheme, which could increase the channel capacity, is the space-division-multiplexing access (SDMA), which assigns channels depending on the space position of the phone. Using SDMA, simultaneous users from different places can use the same carrier frequency, the same time slot, or the same code [1].

Beamforming can be performed as analogue processing, or can be done digitally. Using analogue beam formers can help to reduce the load of digital processing. If there are other digital channelization processes the requirements of speed of the digital processors become very high [2].

A Butler matrix is a beamformer circuit consisting of interconnected hybrid couplers and phase shifters. This matrix requires the least number of couplers compared to the Blass matrix or the Nolen matrix [3]. A Butler matrix is such that a signal into an input port results in currents of equal amplitude on all output ports with a given phase shift. In particular, an N element antenna array requires an $N \times N$ order matrix (N is the number of input or output ports). When an input port of the matrix is excited, a radiation pattern with one single directive beam is generated by the antenna array. However, for applications where more than one port of the matrix needs to be excited to generate adjacent beams, nonpassive circuitry capable of assigning different weights to each input signal is required [3].

Coaxial or waveguide Butler matrices structures can be used to achieve low loss beamforming networks, but such devices are heavy and bulky. Another possibility is the use of high-temperature superconducting (HTS) microstrip structures on high permittivity substrates, which result in low profile and low weight devices. For future generations of mobile communications, such devices could easily be incorporated in HTS transceivers [4]. HTS transceivers for mobile communications have better overall system performance and increased capacity. They include filtering and duplexing functions as well as a cooled low noise amplifier. Even including the cooler, the overall size of the HTS transceiver is such that it could be easily mounted on the top of the mast, close to the antennas, thereby eliminating cable losses that can substantially increase receiver sensitivity and also reduce the transmitter power required from 40 to 2 W [5].

The increased sensitivity of an HTS transceiver, offered by its low insertion loss, allows the base stations to be placed further apart, to have lower radiation power and/or to have longer operation time for given battery power.

Superconducting Butler matrices have previously been realized. In [6], three hybrid couplers are integrated to form a one-to-four beam-forming network designed to operate over the Ku band, from 11.7 to 12.2 GHz. In [7], an eight-beam Butler matrix is built for satellite applications. Peik [7] demonstrates a 16-port matrix at a center frequency of 1.55 GHz, which could be used in satellites for mobile communications such as Globalstar or Teledesic.

Line crossovers have been one of the main drawbacks of a Butler matrix since they may add undesired effects such as increased insertion loss, mismatched junctions, additional line cross couplings, and poor power handling, as well as the increased difficulty of manufacturing them by conventional photolithography. To overcome this problem, several authors have suggested different matrix configurations that do not require

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TABLE I
NUMBER OF COUPLERS AND CROSSOVERS IN A BUTLER MATRIX

Number of ports	Number of 3-dB couplers	Number of crossovers
2x2	1	0
4x4	4	2
8x8	12	16
16x16	32	88
32x32	80	416
64x64	192	1824

crossing lines. One way is to insert a 0-dB directional coupler at the crossover point as in [8] and [9]. Chaloupka [8], [9] built a 4×4 matrix at 9 GHz with four 3-dB couplers and two 0-dB couplers. However, for large matrices, the number of extra 0-dB directional couplers needed for the crossovers becomes very large. To calculate the number of crossovers needed, (1) may be used [8]

$$C_p = 2C_{p-1} + 2^{p-2}(2^{p-2} - 1) \tag{1}$$

where p is the matrix order, which is related to the number of ports by 2^p = number of ports. In (1), p should be equal or greater than 2 and $C_1 = 1$.

Table I shows the minimum number of crossovers needed for an $N \times N$ matrix.

In [2], a beamforming network (BFN) with two integrated diplexers is presented for a frequency of 5 GHz. This BFN uses miniature lumped element branch line (BL) couplers [10]. These couplers are good for narrow-band applications. For a bandwidth of 5%, these couplers have a coupling unbalance of about $+/-0.5$ dB and for a 10% bandwidth, this unbalance increases up to about $+/-$ 1 dB. If wider band BFNs are required, then other kinds of couplers should be used.

A comparison of different architectures of microstrip Butler matrices scaled at the same frequency (2 GHz) and the same substrate is shown in Fig. 1. Fig. 1(a) uses miniature BL lumped element couplers; this configuration shows a very narrow bandwidth due to the coupling characteristics of the coupler and it requires line crossovers. Fig. 1(b) has been suggested in [6]; in this configuration, the crossovers are made by sputtering gold over a dielectric thin film. Fig. 1(d) shows the Butler matrix described in this paper that does not require crossovers. This latter matrix uses conventional BL couplers and slot-coupled (SC) couplers. BL couplers are known to have good performance for bandwidths of around 10% where the coupling unbalance is not greater than about $+/-0.3$ dB and SC couplers operate at even broader bands.

II. PROPOSED BUTLER MATRIX ARCHITECTURE

A commonly used method to make multiple-level Butler matrices has been to pattern two or more boards with different matrix sections and then connecting them together using via-holes. However, for some substrates such as $LaAlO_3$, via-holes are not easy to produce. For this reason, multilayer configurations have been investigated that do not use via-holes. These matrices use two-layer hybrid couplers in combination with planar hybrid couplers.

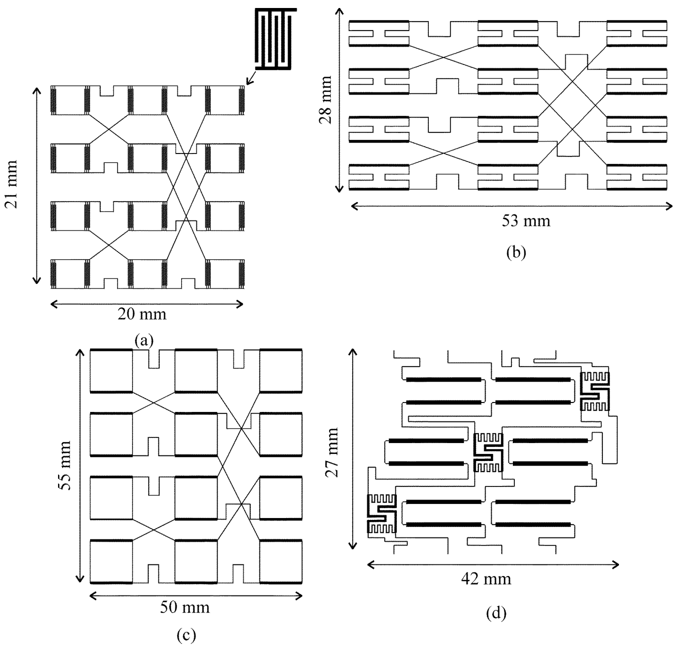


Fig. 1. Different architectures of Butler matrices designed for $LaAlO_3$ at 2 GHz. The black lines show the superconducting microstrip pattern. (a) Uses miniature lumped element BL couplers, (b) uses folded BL couplers, (c) is a conventional Butler matrix with no miniaturization techniques, and (d) is the proposed Butler matrix configuration (only top view). (a), (b), and (c) require line crossovers, whereas (d) is a two-layer configuration.

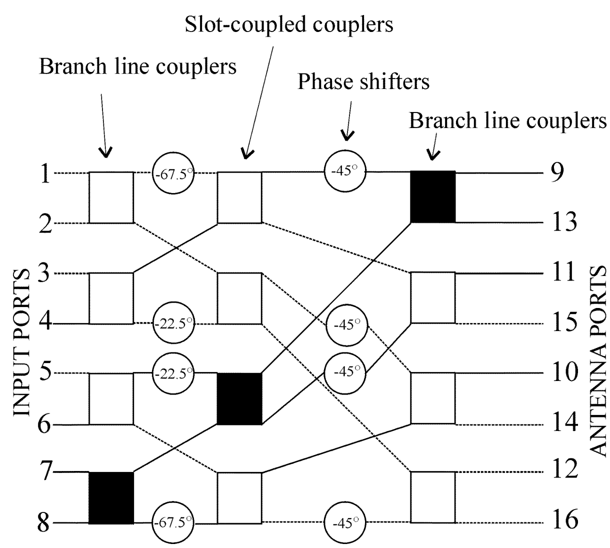


Fig. 2. Block diagram of proposed two-layer configuration. Black components (BL couplers) and black lines are in bottom layer. White components (BL couplers) and dotted lines are in top layer. Gray components are SC couplers in both layers.

The proposed Butler matrix uses 3-dB BL couplers and 3-dB SC couplers [11], [12]. The top layer is coupled to the bottom layer through the SC couplers. A diagram of the proposed Butler matrix configuration is shown in Fig. 2.

III. DESIGN

The matrix was designed at a center frequency of 2 GHz on a $LaAlO_3$ substrate with $\varepsilon_r = 24$ and thickness of 0.5 mm. The superconductor is $YBa_2Cu_5O_7$ (YBCO). All the elements of the matrix (BL, SC couplers, and phase shifters) were designed

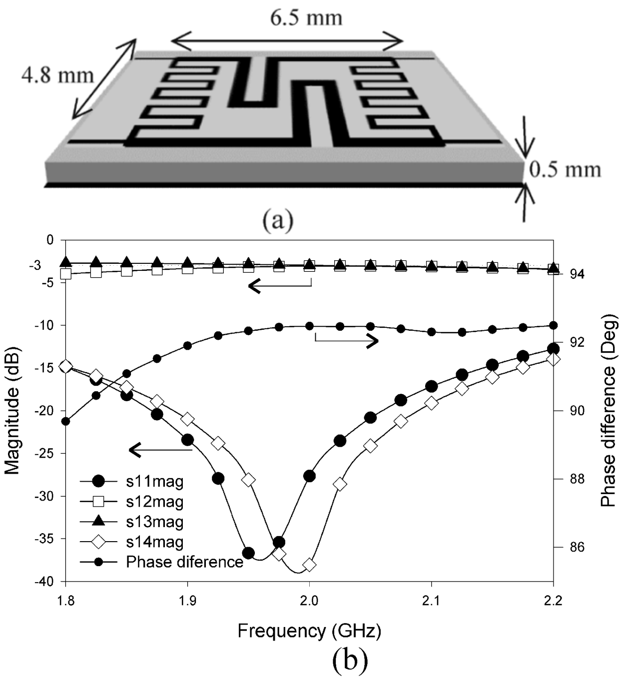


Fig. 3. (a) 3-dB meandered BL coupler on $LaAlO_3$. (b) Simulated response.

optimized and tested separately and then put together to form the final matrix. Each component was simulated and optimized using a Method of Moments software [13], [14].

The branches of the superconducting BL coupler were meandered to achieve a further reduction of size [Fig. 3(a)]. This coupler is three times smaller than a conventional BL coupler on the same substrate, and 30 times smaller than a conventional BL coupler on a low-permittivity substrate ($\varepsilon_r = 2.33$, $h = 0.8$ mm) [15]. Fig. 3(b) shows the response of the meandered BL coupler.

The slot couplers were optimized in a full-wave simulator [13]. It was seen that the overall size, including the coupling slot, of two cascaded 8.3-dB couplers was smaller than a single-section 3-dB coupler. For this reason, the first structure was used for this circuit. Fig. 4(a) shows the layout of this coupler and Fig. 4(b) shows its simulated response.

The meandered lines that form the phase shifters were also simulated and optimized. The best performance for the mitered bend was obtained for a mitering of 85% ($S_{11} = -49$ dB from the simulation). All the elements were then merged together and simulated in HP MDS [14].

The circuit was fabricated using two $2''$ $LaAlO_3$ substrates with $YBa_2Cu_3O_7$ (YBCO) superconducting thin film (0.35 μm thick) deposited on both sides [16]. One substrate was used for the top layer and one for the bottom layer. Each substrate was patterned on both sides, having on one side the circuit layout and on the other side the ground with the coupling apertures. The YBCO ground planes were coated with a thin gold layer to improve the electric contact to a conducting film (Ablefilm 5025, 2-mil thickness) that glues the two substrates to a thin titanium sheet. This sheet is clamped with the titanium box to provide a common ground. Titanium was used due to its good thermal expansion match with $LaAlO_3$. The adhesive conducting film and the titanium sheet were cut to size and coupling holes were punched through. Fig. 5 shows the packaging of the Butler matrix.

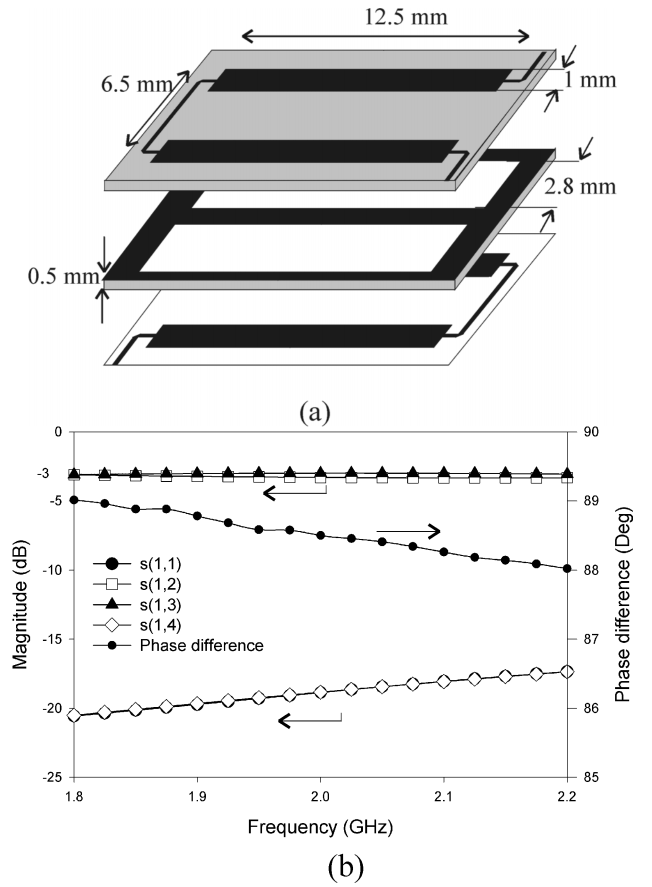


Fig. 4. (a) Two 8.3-dB SC couplers in tandem. (b) Simulated response.

To reduce the size of the box, subminiature push-on connectors [17] were used; these allow adjacent connectors to be as close as 4.3 mm. Fig. 6 shows the final matrix.

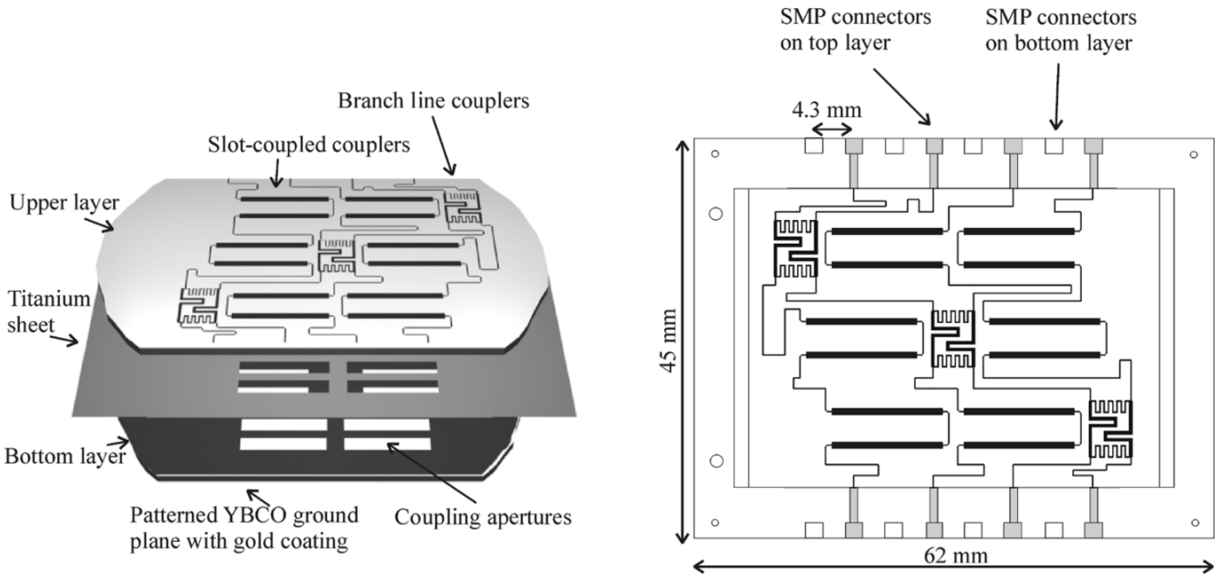
IV. Performance Comparison of the Butler Matrix Using Normal Conductors and HTS

In this section, a comparison of the performance of the miniaturized Butler matrix using HTS at its superconducting state and silver at 300 K is given.

Three simulations were carried out. The first one assumes the circuit and the ground plane to be YBCO (0.35 μm thick). The surface resistance was taken to be $4 \times 10^{-6}\Omega$ [18]. The second and third simulations assume silver (10 μm thick, which is about seven times the skin depth at 300 K) at room temperature and 77 K, respectively, for the circuit and ground plane. The conductivities of silver are $\sigma = 6.17 \times 10^7\ S/M$ at room temperature, and $\sigma = 4 \times 10^8\ S/M$ at 77 K. The loss tangent for the substrate ($LaAlO_3$) is 3×10^{-5}.

Fig. 7(a) shows the simulated response for Input Port 1 of a silver matrix at room temperature. At 2 GHz, the insertion loss is about 1 dB. Fig. 7(b) shows the response for Input Port 1 of the silver matrix at 77 K. At 2 GHz, the average insertion loss is 0.4 dB.

Fig. 8 shows the response for Input Port 1 of the YBCO matrix at 77 K. At the center frequency, the insertion loss is 0.04 dB.



(a) (b)

Fig. 5. (a) Butler matrix showing the two layers. (b) Top view of the Butler matrix in its titanium box.

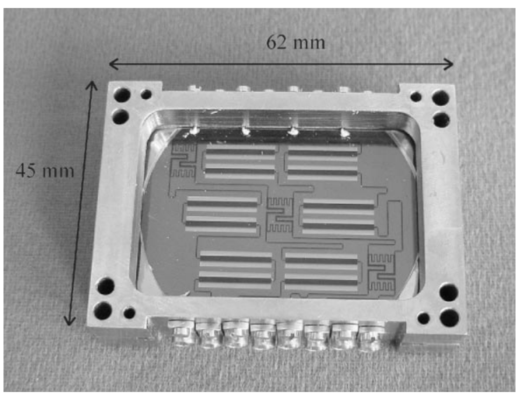
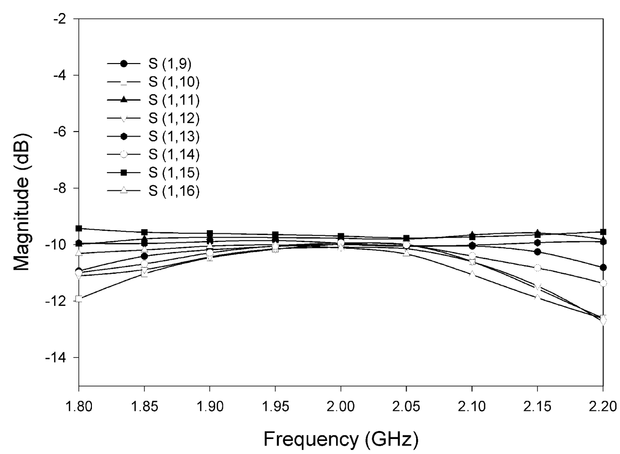
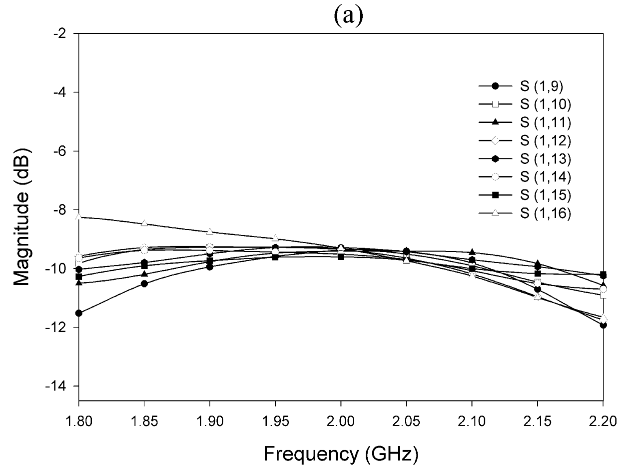


Fig. 6. Two-layer Butler matrix.



(a)



(b)

Fig. 7. Simulation of miniaturized Butler matrix with silver at (a) 300 and (b) 77 K.

This gives an improvement of almost 1 dB for the superconducting matrix compared to silver at room temperature and almost 0.4 dB compared to silver at 77 K.

The total transmitted power of the three (silver and YBCO) matrices can be calculated from the S-parameters by using

$$P_{\text{transmit1}} = |S_{1.9}|^2 P_{\text{in1}} + |S_{1.10}|^2 P_{\text{in1}} + \ldots + |S_{1.16}|^2 P_{\text{in1}}. \quad (2)$$

Solving for the three matrices, the following results are obtained. The silver matrix at 300 K has a $P_{\text{transmit1}} = 0.8 P_{\text{in1}}$; the silver matrix at 77 K gives $P_{\text{transmit1}} = 0.92 P_{\text{in1}}$; and the YBCO matrix gives $P_{\text{transmit1}} = 0.989 P_{\text{in1}}$. The silver matrix at 77-K transmits 18.9% less power than the YBCO matrix and the silver matrix at 77-K transmits 6.9% less power than the YBCO matrix.

In many applications such as two-dimensional scanning, many Butler matrices have to be interconnected and cascaded with each other, making the power saving obtained by using HTS materials crucial. For example, if two matrices were cascaded, the matrices made of silver at room temperature would transmit 64% of the input power, whereas the HTS matrices would transmit 96%.

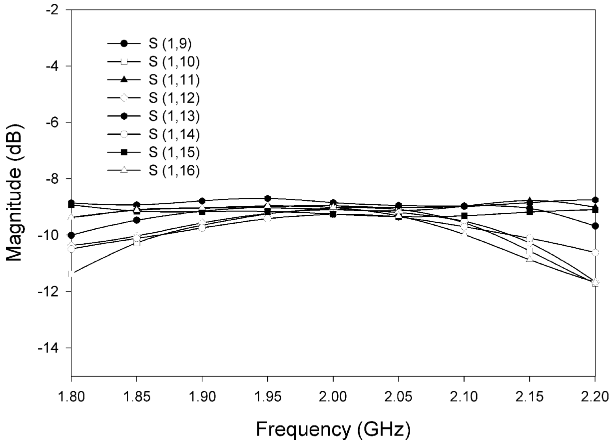
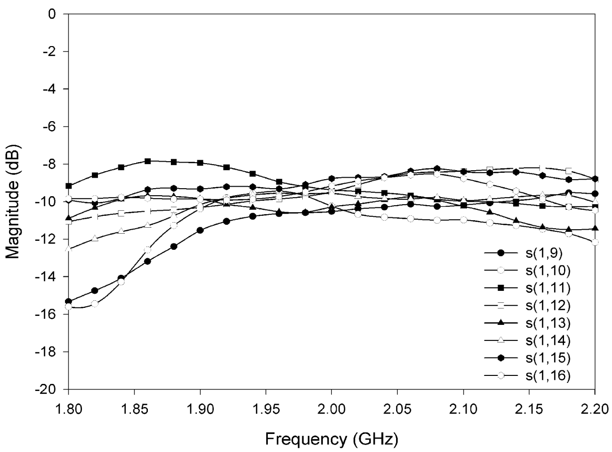
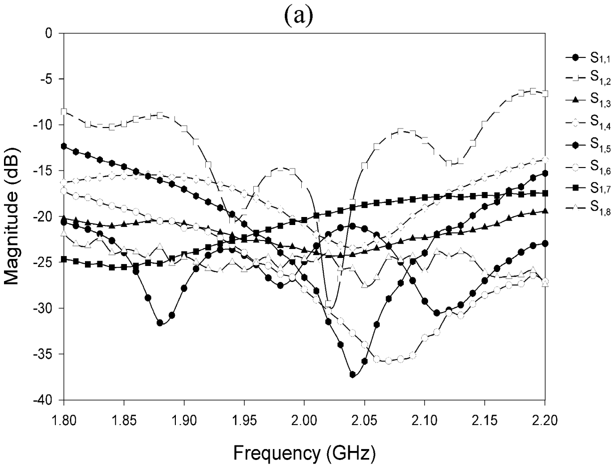


Fig. 8. Simulation of miniaturized Butler matrix with YBCO at 77 K.



(a)

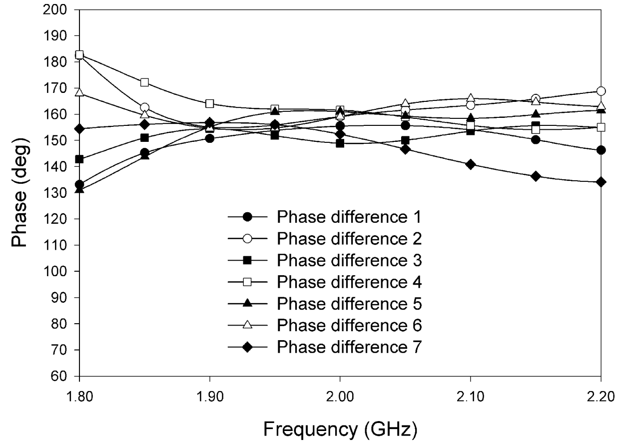


(b)

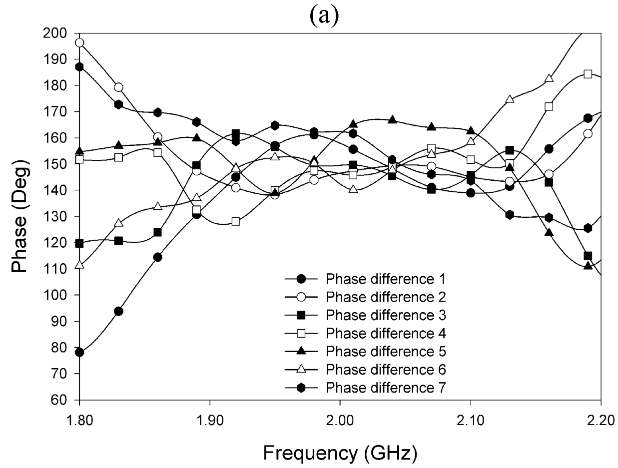
Fig. 9. Experimental results for Input Port 1. (a) Insertion loss and (b) return loss.

V. Experimental Results

The device was cooled down in a low temperature unit consisting of a Grifford–MacMahon closed cycle cryostat, a vacuum pump, a temperature controller, and a refrigerator compressor. The matrix was measured at a power of -10 dBm (which would be suitable for most receive applications) with an HP8720A network analyzer. For a center frequency of 2 GHz, the matrix shows a deviation of about $+/-$ 1.0 dB from the



(a)



(b)

Fig. 10. S-parameter phase difference at the adjacent output ports of Butler matrix when signal is input at Port 2. (a) Simulated results. (b) Experimental results.

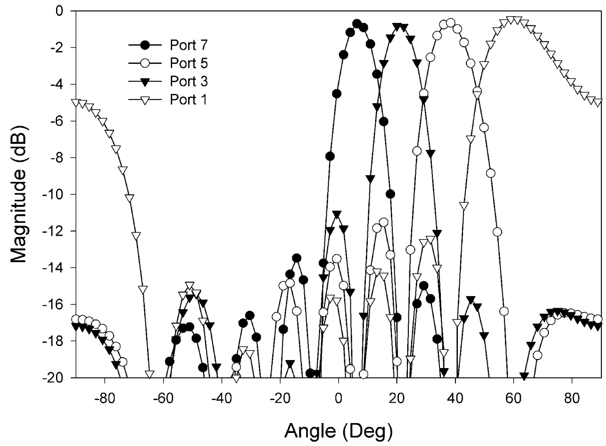
simulation results [Fig. 9(a)]. This deviation can be caused mainly by the misalignment of the two layers, as well as the variations of substrate thickness and substrate permittivity. Another simulation was carried out considering the measured misalignment of the two layers. The experimental insertion loss of the circuit is in average 0.5 dB higher than the simulation results including misalignment, which gives from (3) a transmitted power of about 89% of the input power. A part of the lost power is due to reflection loss [Fig. 9(b)]. To calculate the total reflected power of the Butler matrix, the following is used:

$$P_{\text{reflected}N} = |S_{N1}|^2 P_{\text{in}N} + |S_{N2}|^2 P_{\text{in}N} + \ldots + |S_{N8}|^2 P_{\text{in}N} \quad (3)$$

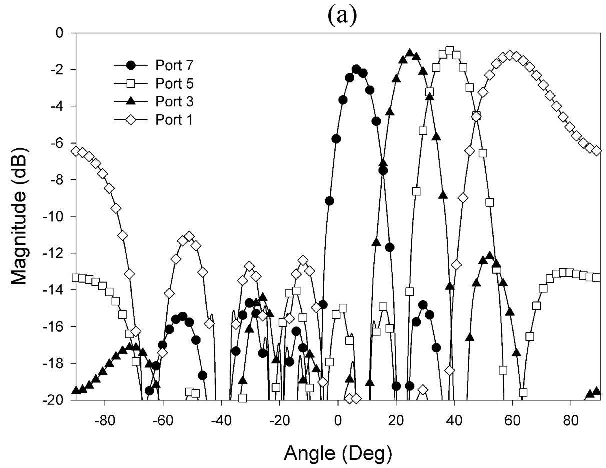
where N is the input port. This gives a reflected power of $P_{\text{reflected1}} = 0.054 P_{\text{in1}}$ at the center frequency.

Fig. 10 illustrates the experimental and simulated results of the phase difference of adjacent output ports, where

$$\text{Phase difference } 1 = \text{Phase}\,(s(1,9) - \text{Phase}\,(s(1,10)))$$
$$\text{Phase difference } 2 = \text{Phase}\,(s(1,10) - \text{Phase}\,(s1,11)))$$
$$\text{Phase difference } 3 = \text{Phase}\,(s(1,11) - \text{Phase}\,(s(1,12)))$$
$$\text{Phase difference } 4 = \text{Phase}\,(s(1,12) - \text{Phase}\,(s(1,13)))$$



(a)



(b)

Fig. 11. Radiation patterns generated when signal is input at Ports 1, 3, 5, and 6. (a) Simulated and (b) experimental results at center frequency (2 GHz).

$$\text{Phase difference } 5 = \text{Phase}\left(s(1,13) - \text{Phase}\left(s(1,14)\right)\right)$$
$$\text{Phase difference } 6 = \text{Phase}\left(s(1,14) - \text{Phase}\left(s(1,15)\right)\right)$$
$$\text{Phase difference } 7 = \text{Phase}\left(s(1,15) - \text{Phase}\left(s(1,16)\right)\right).$$

Using the experimental responses of the matrix, the radiation pattern of the Butler matrix was calculated at the center frequency, assuming eight omni-directional radiating sources spaced $\lambda/2$. As can be seen from Fig. 11 that there is good agreement between the experimental and the simulated results.

VI. Conclusion

An HTS Butler matrix beam-forming network has been described. The Butler matrix in this paper demonstrates the possibility of making HTS Butler matrices without having line crossovers. Multilayer HTS circuits have been implemented. Reasonably good agreement between the simulated results and the superconducting results has been achieved.

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M. J. Lancaster (M'91), photograph and biography not available at the time of publication.