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Design and Simulation of a Microstrip 16x16 Butler Matrix for NR-IFF Radar Application

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Abstract

In this paper, a new microstrip design for the 16x16 Butler matrix is presented. It is well-known that as the number of input/output ports of the Butler matrix increases, so does the number of internal crossovers and thus the complexity of the whole structure increases impractically. Therefore, most reports have been limited to the design and realization of 4x4 and 8x8 Butler matrices. However, in this paper and through the relocation of input/output ports and also by using a two-layer substrate, a new 16x16 Butler matrix is designed to be used in a Non-Rotating IFF radar for the commutation of the active sector of its cylindrical antenna array.

Keywords: Butler Matrix, IFF Radar, Cylindrical Antenna Array

1. Introduction

The identification, friend or foe (IFF) system [1] is a well-established standard that was developed during World War II to identify friendly aircrafts from the foe's on the battlefield via radio communication. It consists of two parts, the interrogator and the transponder, where the interrogator is the asking part transmitting at 1030 MHz and receiving at 1090 MHz and the transponder is the replying part receiving at 1030 MHz and transmitting at 1090MHz. The interrogator is often a ground based station and the transponder is often located on the aircraft. Nowadays, these identification systems are not only used for identification of targets' characteristics, but also for the management of air traffic control [2].

Although the antenna utilized for the interrogator used to be a linear antenna array piggybacked on the primary search radar to be co-rotated mechanically, it can be a cylindrical antenna array as well with its unique scan-invariant pattern characteristics and electronic rotation. Note that cylindrical antenna arrays are popular because of their capability to scan the radiation beam in all angles of the plane of array without any change in their radiation patterns and compared to linear and rectangular arrays they are less sensitive to mutual coupling between the elements. Moreover, the wraparound configuration of the cylindrical antenna array makes it suitable for installations where the antenna should wrap around a tower or a ship mast [3] [4].

In a cylindrical antenna array, the antenna elements remain stationary or non-rotating while the beam is steered electronically to scan the full 360 degrees around the array. Also the beam can be positioned selectively in any direction within microseconds. There are several feeding systems enabling the electronic rotation of a prescribed illumination over a subset of active radiating elements distributed around a cylindrical antenna array (i.e. the commutation of the active sector), however, the most robust antenna architectures satisfying the requirements of reliability are the ones based on the Butler matrix [5].

The Butler matrix [6] is one of the most important parts of a cylindrical antenna array, specifically for the electronic rotation of the main beam and the permutation of the amplitudes and phases applied to the radiating elements during the commutation of the active sector around the array [7]. But as is well-known, the increase in the number of input and output ports of the Butler matrix, which is inevitably accompanied by the increase in the number of internal hybrid couplers and crossovers, makes the design and realization of this type of structure cumbersome, especially in the dimensions of 16x16 and beyond. So a simple search in the available sources reveals that almost all the available articles and reports are limited to the design of 4x4 and 8x8 Butler matrices.

If in the conceived structure for the IFF radar's interrogator, a 64-element cylindrical antenna array is assumed and if the active sector is assumed to consist of 16 elements, then the electronic rotation of the radiation pattern around the array can be realized with the help of a 16x16 Butler matrix plus sixteen SP4T switches [3].

Regarding the design of the 16x16 Butler matrix, in [8] it has been tried to overcome the problem of many crossovers of this type of structure with the help of two back-to-back microstrip boards and thus a two-layer 16x16 Butler matrix is presented to be used in the frequency range of 25GHz to 30 GHz. It is worth mentioning that in the proposed structure in [8], the number of existing crossovers has been substantially reduced from 85 to 12.

In [9] and in order to avoid the problematic crossovers, the 16x16 Butler matrix structure is divided into several sub-sections and by separately designing and connecting these sub-sections through coaxial cables, a somehow 3D structure for use in the frequency range of 1.65 GHz to 2.17 GHz is presented.

In [10] and similar to what is sometimes suggested for 4x4 and 8x8 Butler matrices (as in [11]), it has been tried to change the topology of the structure and relocate the positions of the input and output ports around the PCB in order to avoid the occurrence of the problematic crossovers as much as possible. Thus the number of the crossovers has been reduced to only four and finally a structure for use in the frequency range of 9 GHz to 11 GHz is presented.

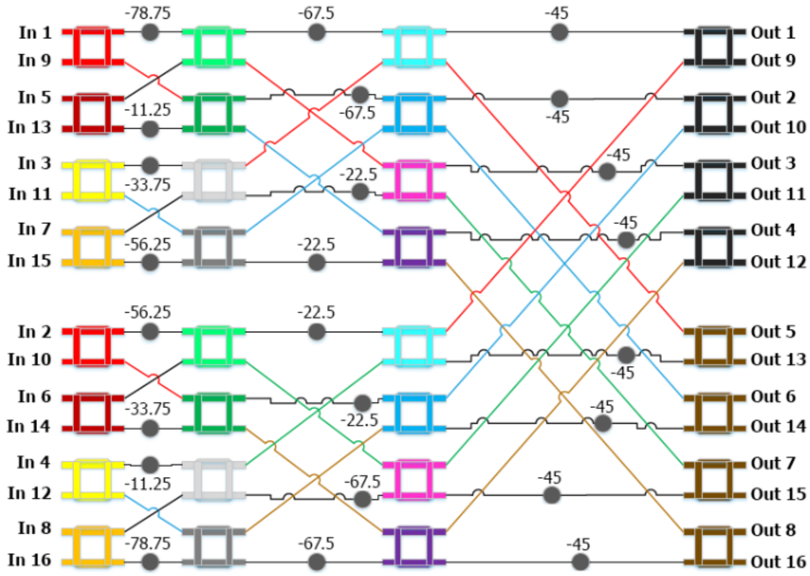

Fig. 1. Block diagram of 16x16 Butler matrix (numbering of input and output ports is in accordance to what is required for use of rotational mechanism of Butler matrix [3])

In this paper the design and simulation of the 16x16 Butler matrix is dealt with as well; and with a combination of the above methods, that is the relocation of the input and output ports of the Butler matrix and the use of two-layer microstrip boards we will try to avoid the occurrence of the problematic crossovers as much as possible. Thus, in Section II the new topology based on the relocation of input/output ports is presented. Then in Section III a new miniaturized wideband hybrid coupler is introduced in order to save as much space on the PCB as possible while obtaining a bandwidth as wide as possible. Then in Section IV the design and simulation of a 16x16 Butler matrix is discussed, and the simulation results related to the amplitudes and phases of the scattering parameters in all the input and output ports are presented. Finally a conclusion is drawn in Section V and the references are listed in Section VI.

Note must be made that since the desired Butler matrix is intended to be used in the interrogator part of an IFF radar, the design frequency is set to be 1060 MHz and Rogers 4003 substrate with a dielectric constant of 3.55

and a thickness of 60 mil is used. It should also be noted that due to the mentioned design frequency, which leads to relatively large dimensions for different parts of the structure, we are also facing limitations in choosing the dimensions of the PCB board, and therefore, in addition to the above methods, we will also use the common miniaturization techniques such as meandering to fit the entire structure in the largest PCB board available in the market, which is 610x457 mm^2.

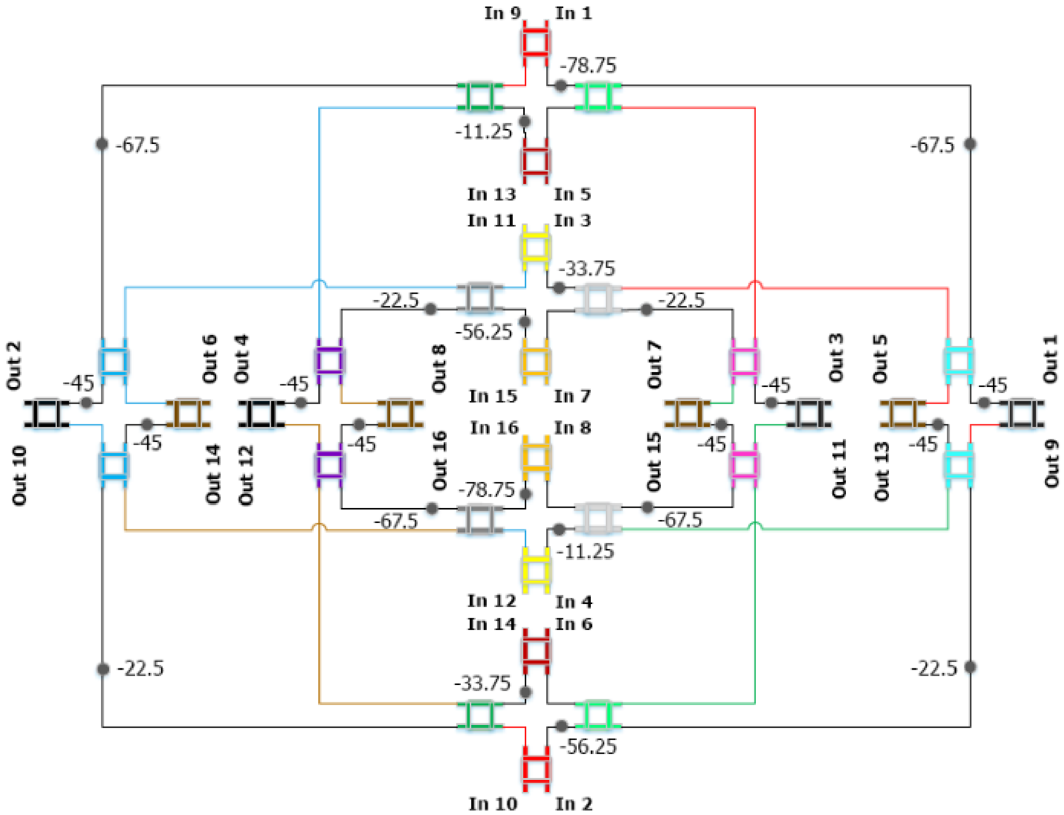

Fig.2. Relocation of input and output ports

2. Relocation of the Input and Output Ports of the Butler Matrix

As mentioned and also presented in [10] and [11], in this section, it is tried to reduce the number of the crossovers as much as possible by moving the location of the input and output ports of the Butler matrix around the PCB. It is very important to note that in this paper, the numbering of the input and output ports is in accordance to what is required for the correct application of progressive phase shifts and the use of the rotational mechanism of the Butler matrix [3].

Fig.1 shows the block diagram of a 16x16 Butler matrix. As can be seen in Fig.2, by changing the location of the hybrid couplers, the number of problematic crossovers can be reduced dramatically [10].

The main problem in the realization of the above structure (even in spite of the significant reduction in the number of crossovers to only four) is the relatively long wavelength at the frequency of 1060 MHz, which makes it impossible to construct the above structure on the available microstrip boards in the market with the dimensions of only 610x457 mm^2. Therefore, we chose to design the structure on a two-layer board and use RF vias to transfer the waves between the layers. Of course, the elimination of the remaining four crossovers is an advantage too.

3. Design and Simulation of Hybrid Couplers

By relocating the positions of the input and output ports of the Butler matrix and subsequently removing the interfering crossovers, the only remaining important part is the 90°/3-dB hybrid coupler that needs to be designed.

To this end, first a hybrid coupler was designed in HFSS software. Then as mentioned in Section I since we face bandwidth limitation when designing the main structure of the Butler matrix through using a large number of couplers, from the very beginning we opt for the wideband hybrid couplers as presented in Fig. 3 [9].

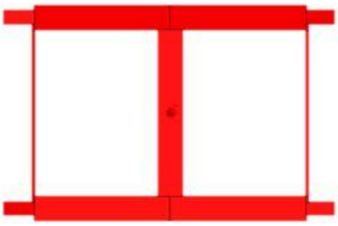

Fig.3. Structure of wideband 3-dB hybrid coupler

As it was said, because we are facing space limitation on the microstrip boards available in the market, next we try to make the structure of the wideband hybrid coupler as small as possible with the help of the meandering as shown in Fig. 4. It should be noted that with the help of miniaturization technique, the dimensions of the wideband hybrid coupler were reduced from about 81x58 mm^2 to about 63x56 mm^2 (the length of the 50-Ohm lines related to the ports is not included). The amplitudes and phases of the proposed miniaturized structure are shown in Fig.5 and Fig.6 respectively.

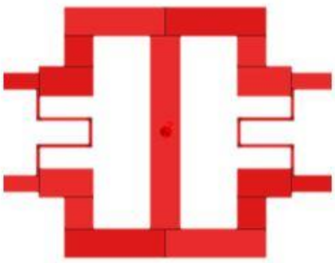

Fig.4. Miniaturized structure of wideband 3-dB hybrid coupler

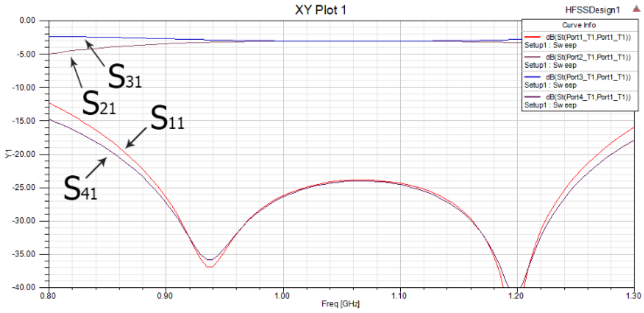

Fig.5. Amplitudes of scattering parameters of miniaturized wideband hybrid coupler

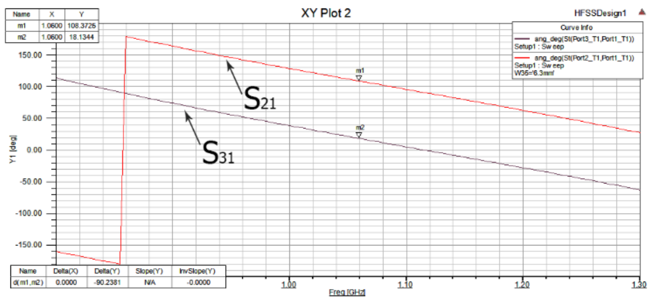

Fig.6. 90-degree phase difference between the 2nd and 3rd ports of miniaturized wideband hybrid coupler

4. Design and Simulation Results of Butler Matrix

By rearranging the locations of the input and output ports of the Butler matrix and using miniaturized wideband 3-dB hybrid couplers, a 16x16 Butler matrix was designed on a two-layer Rogers 4003 board with dimensions of 610x457 mm^2, and the results related to the amplitudes and the phases of scattering parameters for each port are given in Figs. 11 to 26. Unfortunately, due to space limitations, only half of the graphs have been able to be presented in this paper. Also, in order to make it possible to use SMA connectors, the entrances of the ports on the upper layer have been rotated by 90 degrees.

As can be seen in Figs. 11 to 18, specifically in the frequency range of 1020 MHz to 1100 MHz, the return losses of the input ports are limited to below -20 dB, and the amplitudes of the scattering parameters for all the output ports are about -12.04 dB, which shows that the power is almost evenly distributed among all the sixteen output ports.

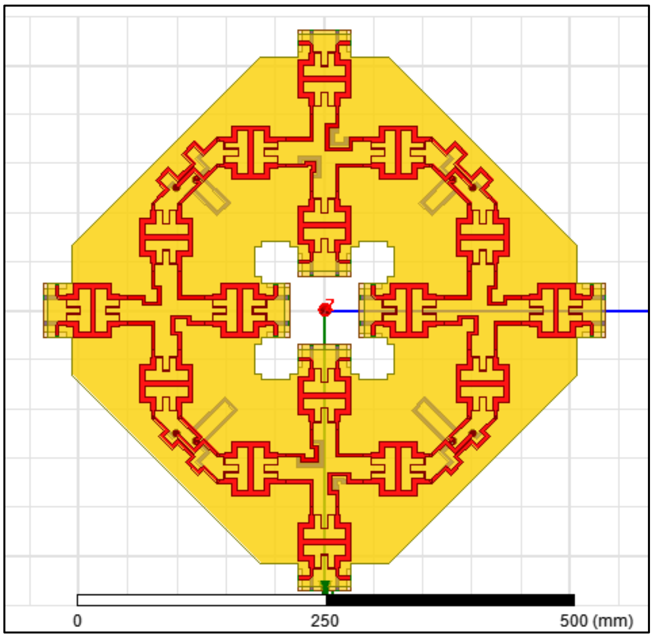

Fig.7. Upper layer of proposed 16x16 Butler matrix

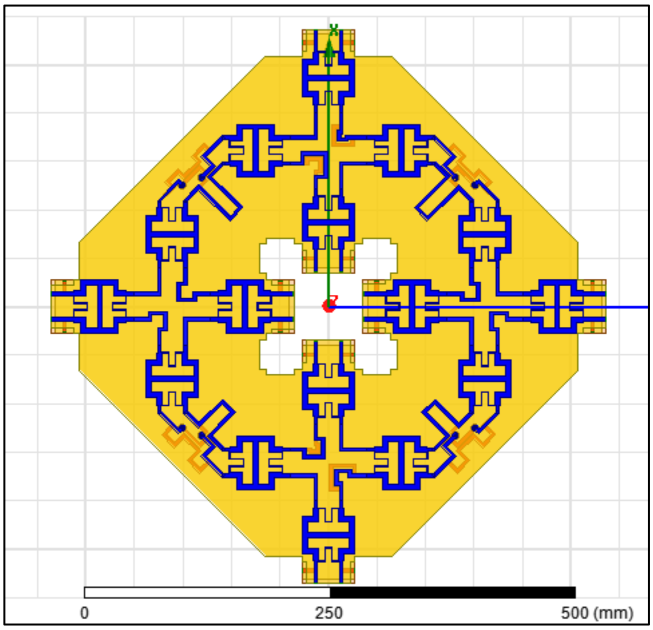

Fig.8. Lower layer of proposed 16x16 Butler matrix

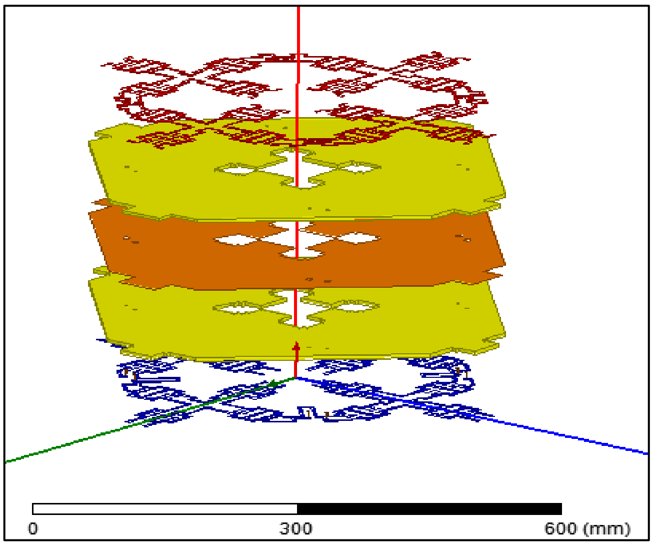

Fig.9. Exploded view of proposed 16x16 Butler matrix

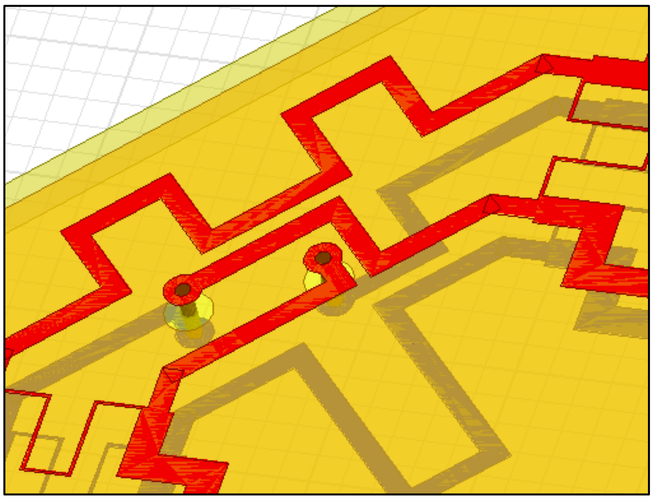

Fig.10. Crossovers in proposed 16x16 Butler matrix

5. Conclusion

In this paper and through the relocation of input/output ports and also by using a two-layer substrate, a new 16x16 Butler matrix is designed to be used in a Non-Rotating IFF radar for the commutation of the active sector of its cylindrical antenna array.

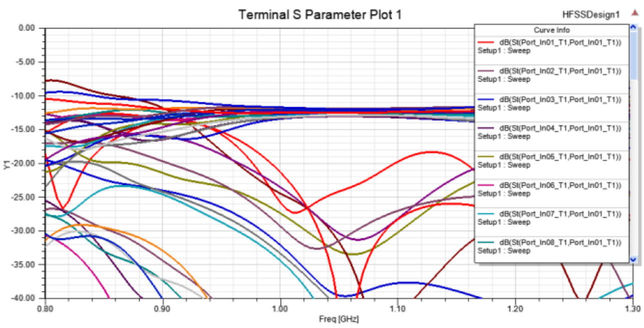

Fig.11. Amps of S parameters when fed by input port No.1

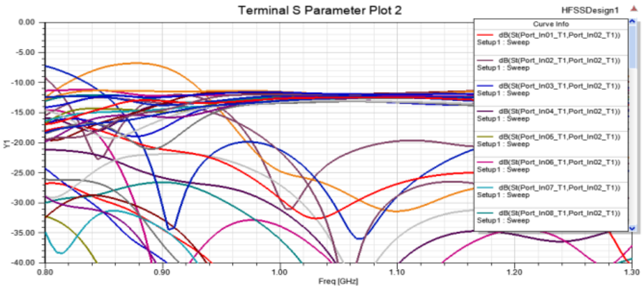

Fig.12. Amps of S parameters when fed by input port No.2

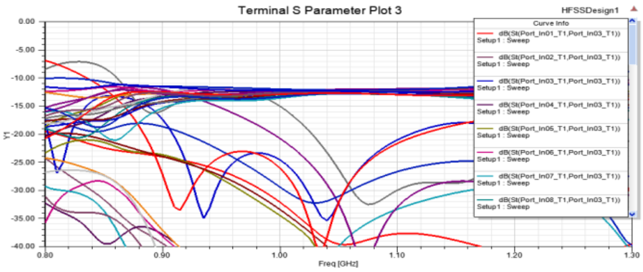

Fig.13. Amps of S parameters when fed by input port No.3

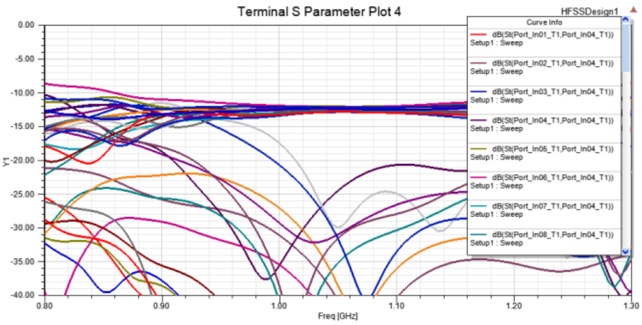

Fig.14. Amps of S parameters when fed by input port No.4

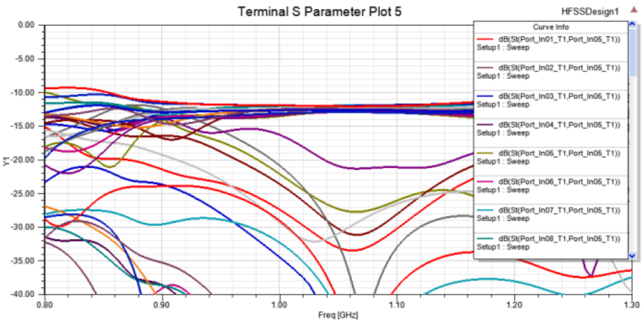

Fig.15. Amps of S parameters when fed by input port No.5

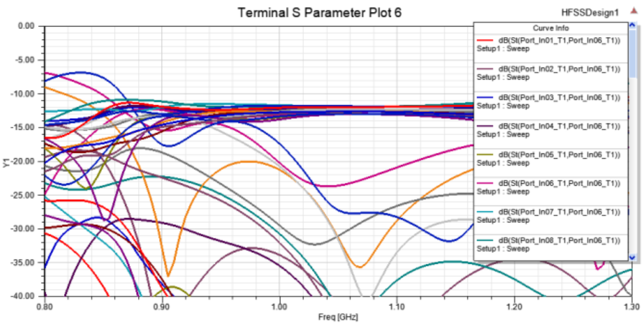

Fig.16. Amps of S parameters when fed by input port No.6

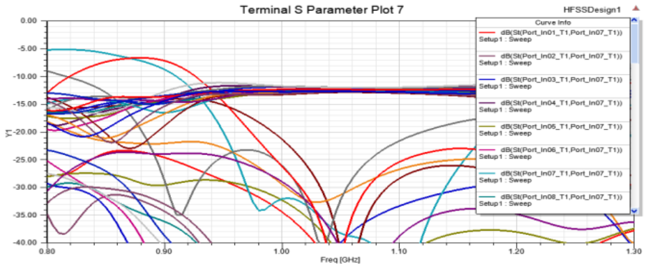

Fig.17. Amps of S parameters when fed by input port No.7

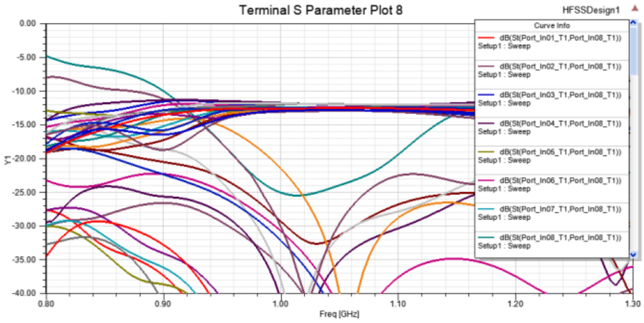

Fig.18. Amps of S parameters when fed by input port No.8

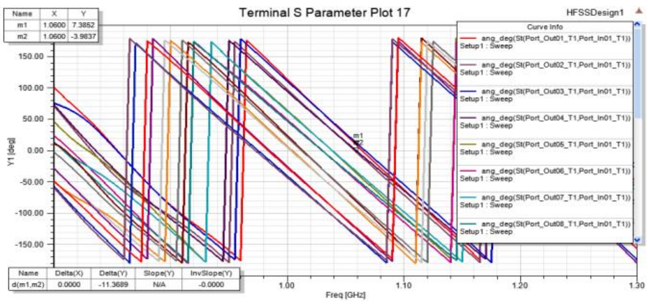

Fig.19. Phases of S parameters of output ports when fed by input port No.1

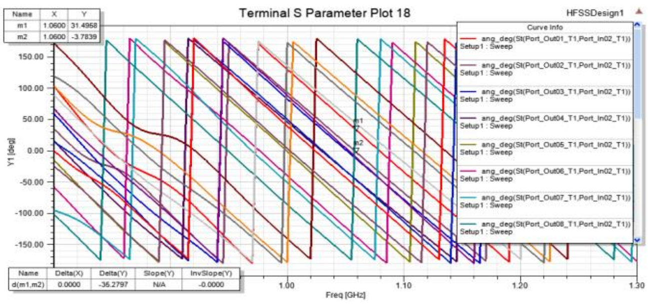

Fig.20. Phases of S parameters of output ports when fed by input port No.2

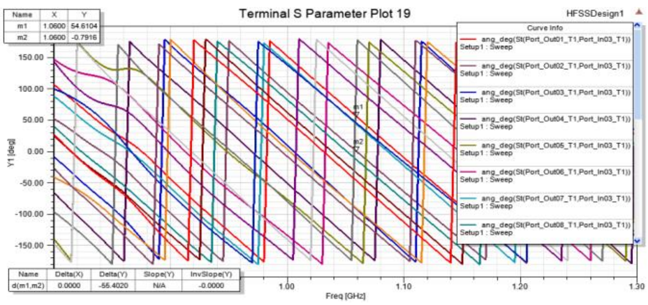

Fig.21. Phases of S parameters of output ports when fed by input port No.3

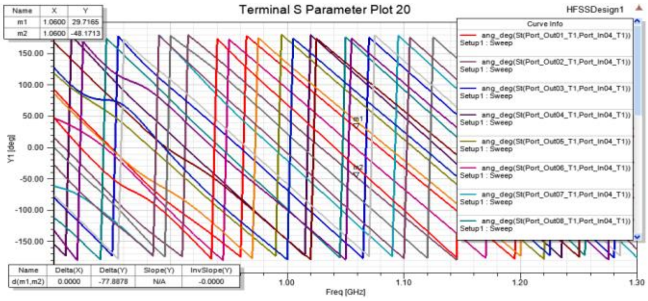

Fig.22. Phases of S parameters of output ports when fed by input port No.4

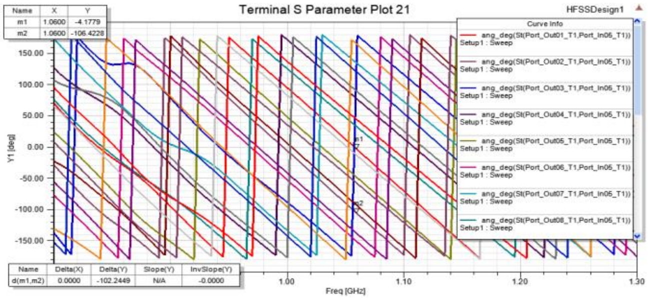

Fig.23. Phases of S parameters of output ports when fed by input port No.5

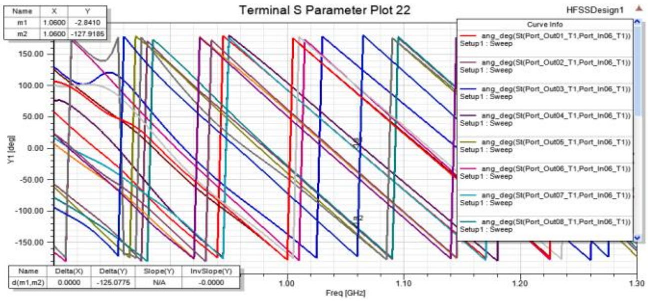

Fig.24. Phases of S parameters of output ports when fed by input port No.6

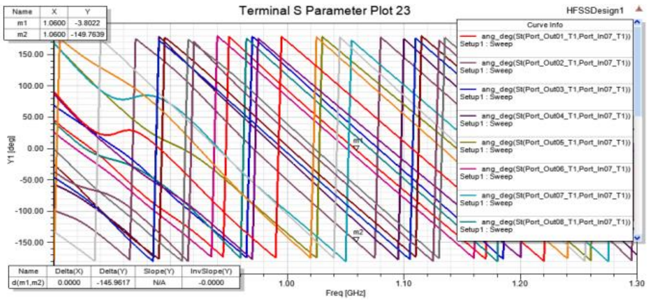

Fig.25. Phases of S parameters of output ports when fed by input port No.7

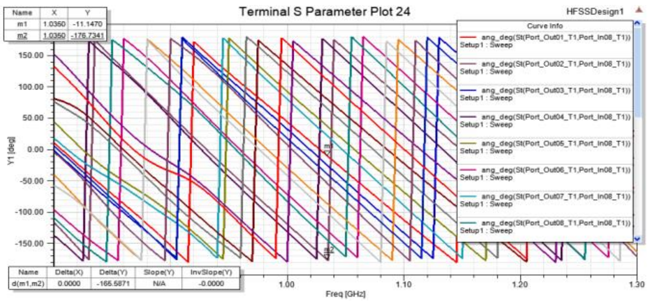

Fig.26. Phases of S parameters of output ports when fed by input port No.8

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