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RESEARCH PAPER

A programmable compact wide-band RF feed network

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The design and fabrication of a wide-band programmable radio frequency (RF) feed network is proposed. It is designed to cover a wide band from 2.5 to 6 GHz over two separate branches. The feed network is simulated and fabricated on an FR-4 substrate with 0.8 mm thickness. Good matching between simulation and measurement results is achieved. The measured amplitude resolution was 0.5 dB with a maximum error of 0.22 dB. The measured phase resolution was approximately 5.6° with 1° maximum error. This design is a generic one that can be used in any kind of RF or antenna systems.

Keywords: Feed network, Broad-band, Programmable, Antennas

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I. INTRODUCTION

Radio frequency (RF) feed networks are essential in any multi-antenna or multi-line microwave system. Such networks are used in antenna arrays to perform beamforming (BF) and null steering (NS). The control of the beams/nulls is achieved by changing the relative amplitudes or phases or both between different antenna elements. RF beamformers are either networks or quasi-optical lenses. The main difference between them is that the beam angles are fixed (independent) with frequency changes in lenses, while they change with frequency in network-based beamformers. From this fact, lenses are considered wide-band while networks are narrow-band. The Butler matrix is an example of a network beamformer, whereas the Rotman lens is a quasi-optic one. These two are the most popular ones and have many practical applications.

The Butler matrix [1] consists of hybrid couplers, phase shifters, and crossovers. It has a simple structure for small number of beams. However, since it has crossovers, a multi-layer structure is required for large number of beams (larger number of inputs/outputs). The beam ports are usually isolated and the number of beams are typically a power of two. A four-beam Butler matrix feeding a four-square monopole array was presented in [2] and covered a range of frequencies from 2.4 to 3.4 GHz. Another matrix fabricated using MMIC technology was developed in [3]. It was packaged on a chip of size 1.36 × 1.47 mm^2 that works only at 2.4 GHz.

In [4], a combination of a conventional Butler matrix and tunable phase shifters was introduced to improve the beam resolution. The tunable phase shifters were responsible only for steering the beam in the range between two adjacent beams that were created using a Butler matrix. The overall circuit size was 175 × 135 mm^2 with a full scanning range of 108° It operated between 1.6 and 2.8 GHz. An approach based on vector modulation to achieve controlled phase shifting for BF applications was presented in [5]. This technique is performed on the *I*/*Q* components of the signal and suffers from high complexity. It also operated within limited frequency bands. While in [6] a compact six-bit programmable phased array front end was proposed but for frequencies covering 24 GHz.

A Rotman lens [7] is a true time-delay beamformer and hence the beam angles are independent of frequency. It has complex design parameters. The Rotman lens can provide low sidelobes (as low as −33 dB) [8]. A 2.4 GHz Rotman lens was designed in [9] for multiple-input and multiple-output (MIMO) applications. It provided a four-beam lens and generated four scanning beams. Its frequency of operation was 2.4 GHz and occupied a size of 19.3 × 22.3 cm^2 An 8 × 8 Rotman lens was developed in [10] to be used in vehicle-to-vehicle communications systems. It occupied a size of 359.1 × 258 mm^2 and operated at 3.15 GHz.

As noticed from the previous work, network beamformers have easy structures for small number of beams. But for a large number of beams, the design will be very complicated especially for crossovers and the directional couplers that need multilayer structures. Also, most of them are valid only for narrow band applications. Network beamformers can only provide a certain number of beams that are pre-defined and cannot be changed. So, it is difficult to reprogram them to cover other angles. The side-lobes in such networks are relatively high because they do not have amplitude control capability. Lens-based beamformers provide wider frequency coverage but with larger dimensions. They have good isolation between their ports. It is difficult to achieve linear progressive phase with lenses due to their complicated curvature structure. Finally, all of the programmable feed networks for antenna

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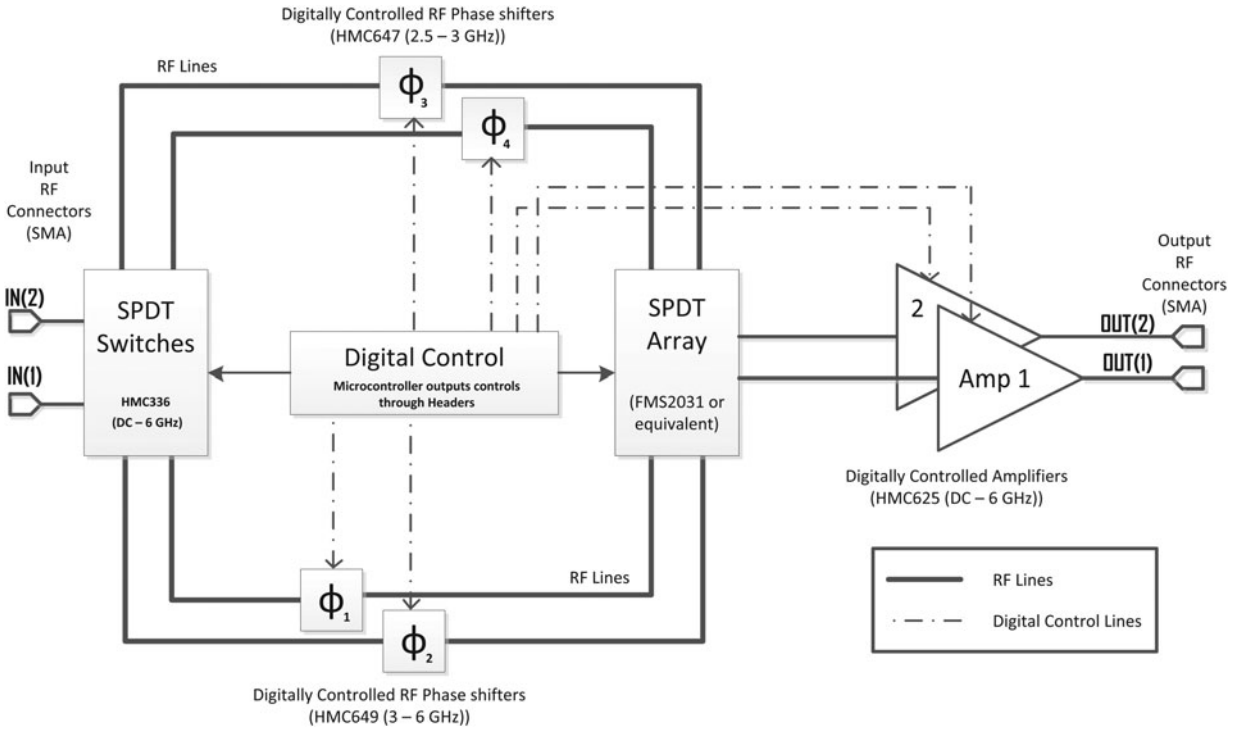


Fig. 1. Design architecture of the proposed programmable feed network.

array applications were realized at very high frequencies (i.e. higher than 10 GHz).

To come up with a wideband feed network that is digitally programmable with high resolution in amplitude and phase as well as compact in size is a relatively challenging task. In this work, we propose a digitally controlled programmable wideband RF feed network that covers the frequency band from 2.5 to 6 GHz. A complete path of the network occupies

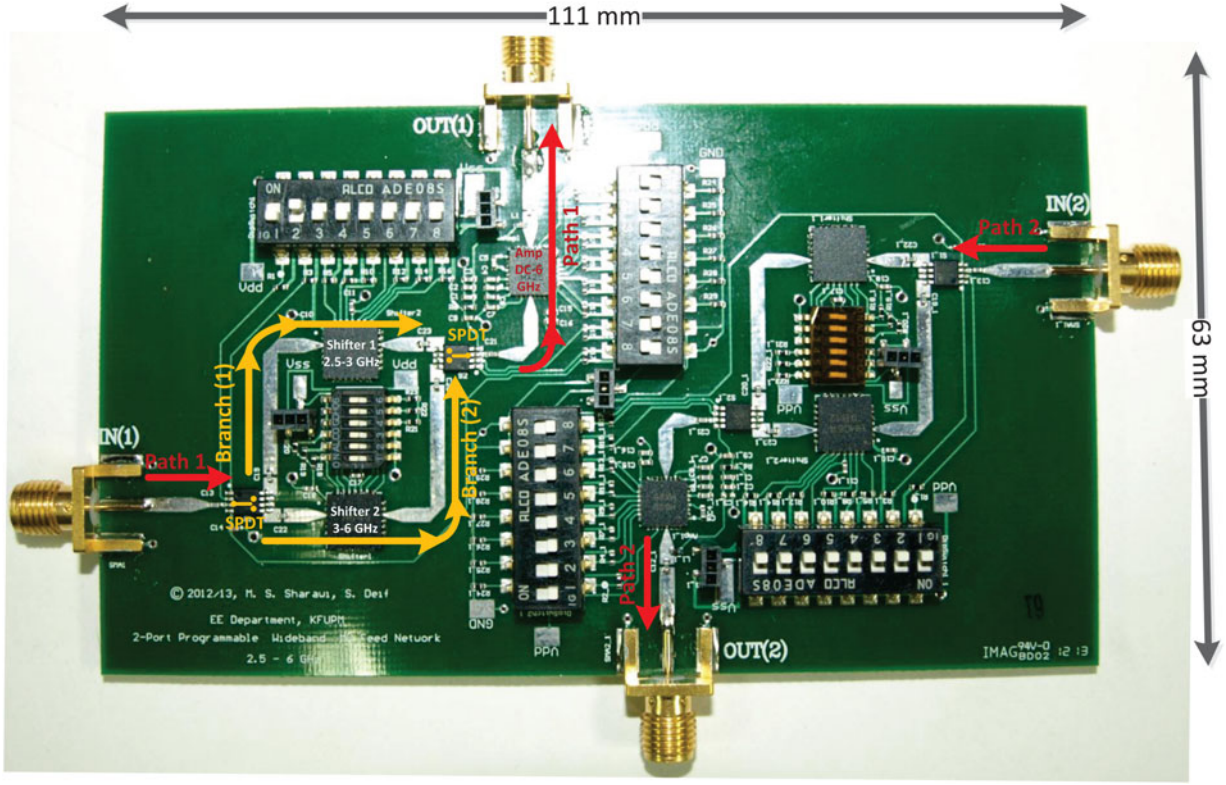


Fig. 2. Fabricated board of the proposed two-path network (to feed two antennas).

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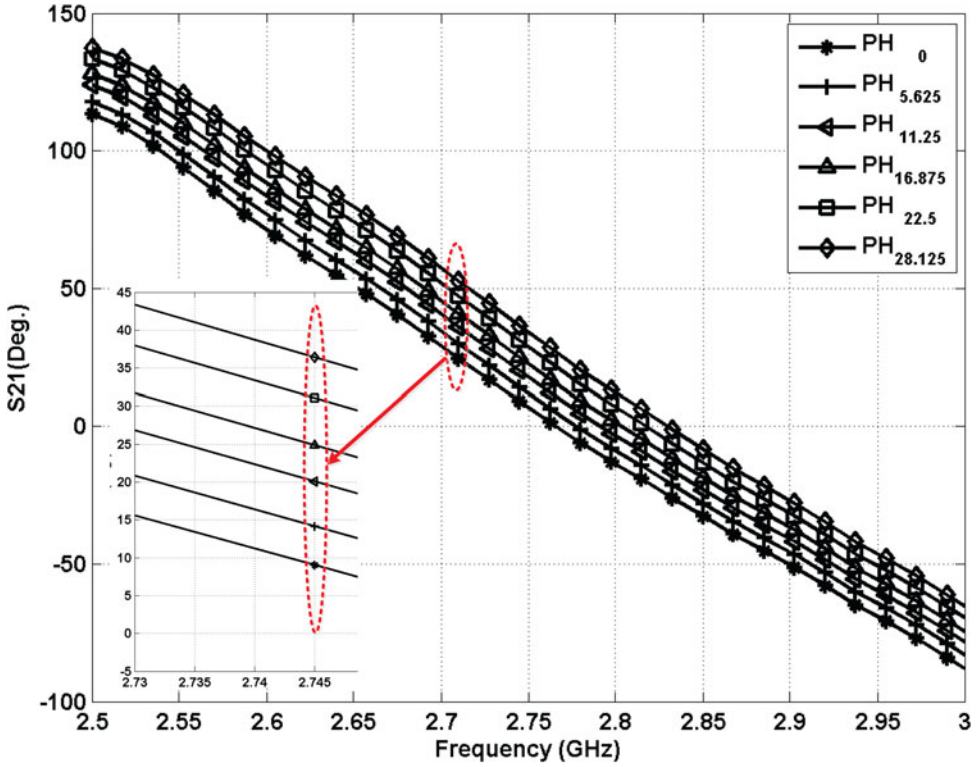


Fig. 3. Measured phase results with 5.6° step (2.5–3 GHz).

70 × 51 mm² and two paths occupy 111 × 63 mm² (i.e. to feed two antennas). The design architecture will be explained in Section II. The fabricated design followed by the measured results are described in Section III. Conclusions are stated in Section IV.

II. DESIGN ARCHITECTURE

As shown in Fig. 1, the design architecture of the proposed two-path feed network is composed of four main stages; RF switching, phase shifting, amplification, as well as the digital

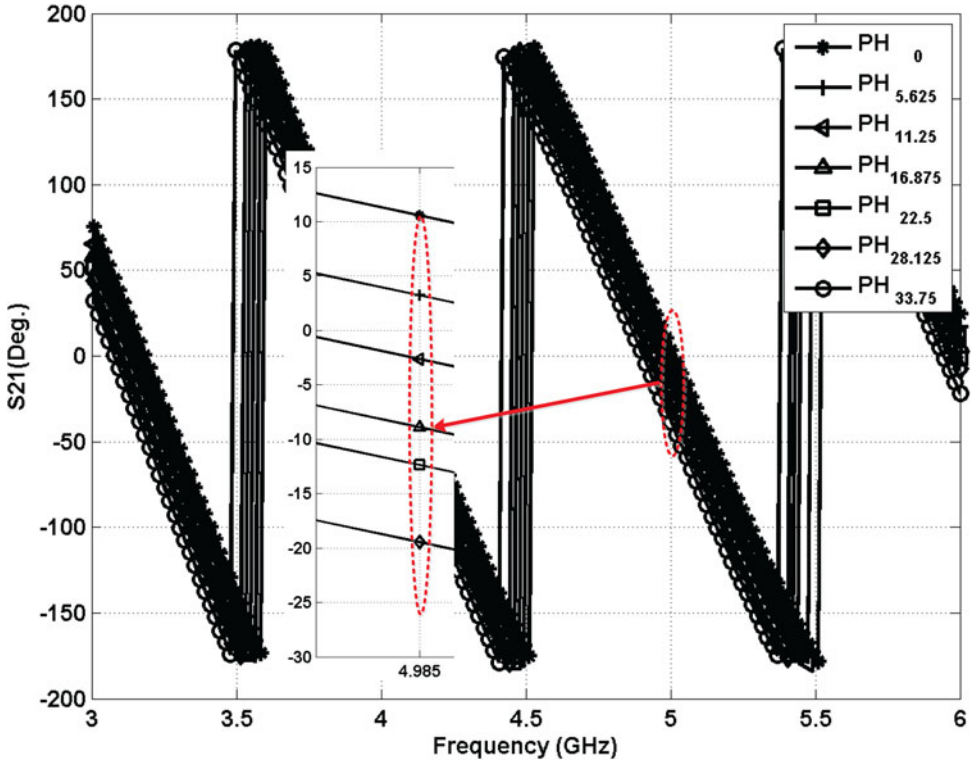


Fig. 4. Measured phase results (7 curves.) covering 0–33.75° in 5.6° steps (3–6 GHz).

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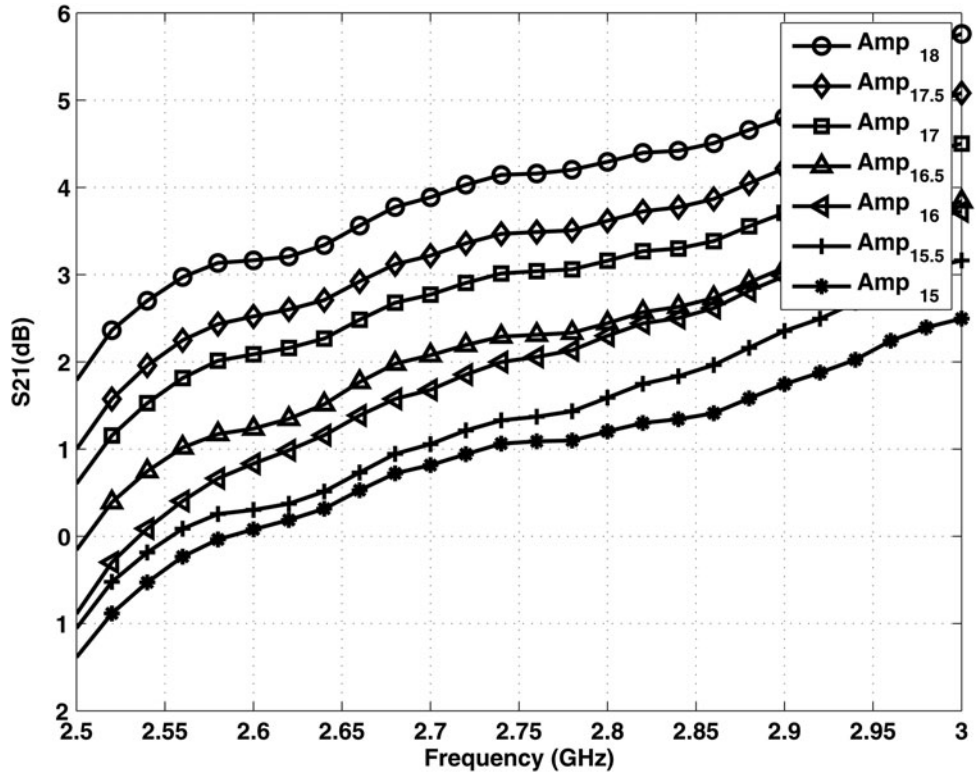


Fig. 5. Measured amplitude results with 0.5 dB steps (2.5–3 GHz).

control. The wideband coverage is achieved through two separate branches, one covered the frequency range from 2.5 to 3 GHz and the other covered 3–6 GHz. Two switching stages were used at the input and output sides of the phase shifters. A broadband GaAs MMIC single-pole double-through (SPDT) non-reflective switch was used. The switch covered the range from DC-6 GHz and high isolation (42 dB at 6 GHz) and low insertion loss (1.6 dB at 6 GHz). The

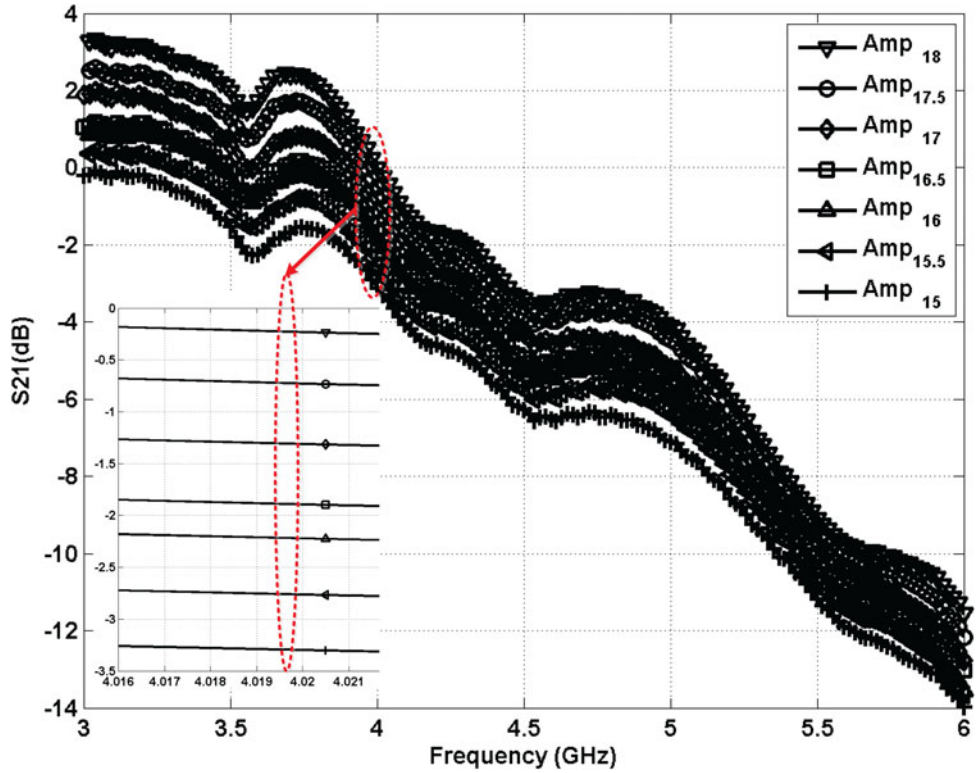


Fig. 6. Measured amplitude results with 0.5 dB step (3–6 GHz).

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switching time was typically 20 ns. GaAs MMIC six-bit digitally controlled phase shifters that provide 360° of phase coverage with phase resolution of 5.625° were used. The first one (HMC647) covered the lower frequency range (2.5–3 GHz) and the second-phase shifter (HMC649) covered the higher frequency range from 3 to 6 GHz. Once the phase shift is imposed on the incoming signal, a GaAs MMIC six-bit digitally controlled variable gain amplifier is used for amplitude control. The amplifier covers the range from DC to 6 GHz and can be programmed to provide anywhere from −13.5 to 18 dB of gain in 0.5 dB increments. The amplifier does not have a flat gain versus frequency response. It has a maximum gain of 18 dB that decreases to about 5 dB at 6 GHz. The amplifier has two modes of operation, serial and parallel. The parallel mode was used to guarantee the fastest response for the amplifier (12 ns response time compared to 0.8 μs for the serial mode). The chosen components were picked based on their size and resolution since high resolution as well as compact size were of the design requirements.

III. RESULTS AND DISCUSSIONS

The fabricated board is shown in Fig. 2. It consists of two paths that can feed two antennas. Since we have two phase shifters in each path to cover the whole range, each path has two branches. The paths are identical and occupy very small area to minimize the board size. The dip-switches consume most of the board size because each main component (phase shifter and amplifier) has a separate dip-switch that cannot be shared. These switches can be replaced by headers or a main digital control unit such as a Microcontroller to reduce the size and integrate the proposed feed network in a system level solution.

The board was built on an FR-4 substrate material with 0.8 mm thickness and relative permittivity (ε_r) of 4. The total size of the two-path feed network was 111 × 63 mm². Measurements were conducted using an Agilent N9918A vector network analyzer (VNA). The phase changes with typical steps of 5.6° are shown in Fig. 3. Measured and simulated results were in very good agreement. The maximum measured step was 6.7° and the minimum one was 4.6° with an error of +1°. The proposed network provides this step resolution over the whole frequency band, from 2.5 to 3 GHz in Fig. 3, and from 3 to 6 GHz as shown in Fig. 4. For a linear array feed, a scanning beam of resolution 1.8° can be achieved using these steps. This provides finer resolution and more flexibility compared to that obtained from [4] at the expense of using extra electronics (the microcontroller unit). In addition, the complexity of the proposed design is much lower than that of [5].

Figures 5 and 6 show the amplitude changes with a resolution of about 0.5 dB per step, with a maximum error of 0.22 dB in the two bands, respectively. The amplifier has a maximum gain of 18 dB and goes down to −13.5 in 0.5 dB increments and 64 steps (six-bit control). The maximum achieved gain in the 2.5−3 GHz was 5.5 dB due to the combined insertion loss from the other components (typical losses of 11 dB without RF lines and bends). A linear phase response was obtained. Thus, the phase resolution from the phase shifters will not be affected by the amplifier amplitude changes. Figure 7 shows the phase response of the design for different amplitude steps. A phase stability of <+ 1° is achieved over a wide range of amplitudes. In addition, amplitude stability is achieved. Figure 8 shows how the amplitude

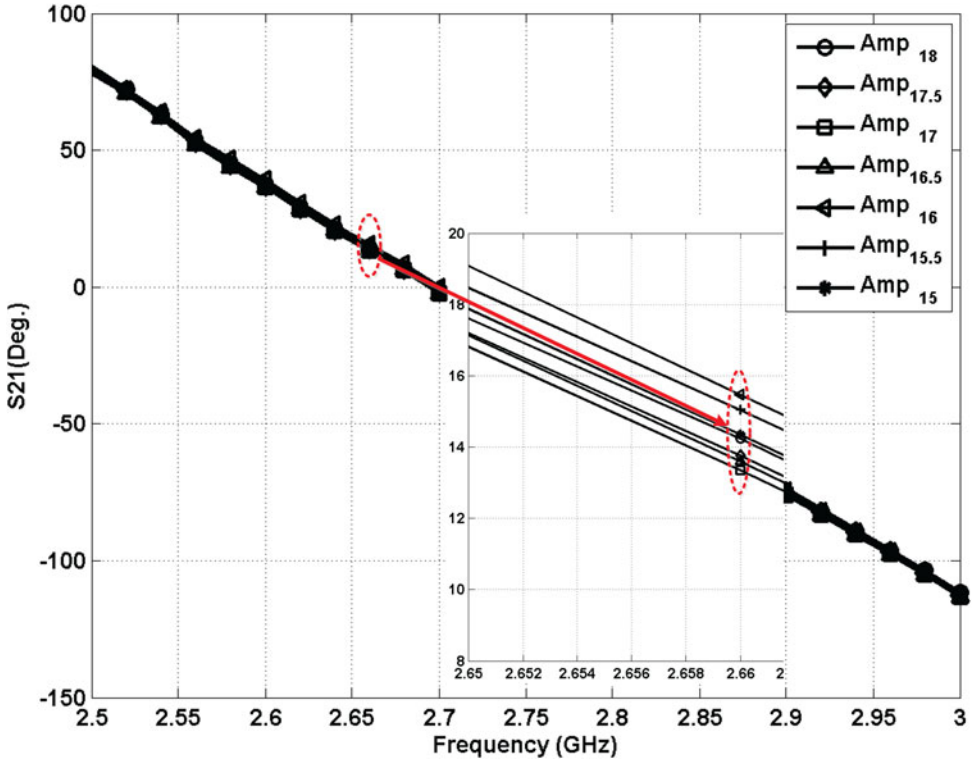


Fig. 7. Phase response for amplitude changes.

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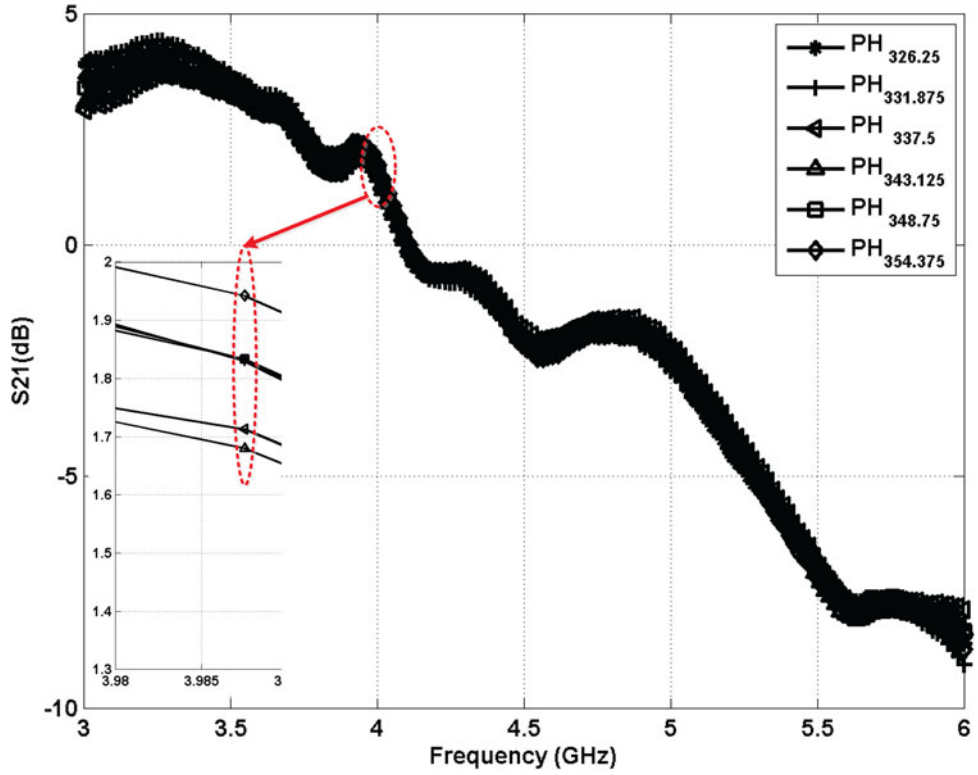


Fig. 8. Amplitude response for different phase changes (18 dB gain step).

does not change with different phase steps. The amplitude error was $<$0.15 dB.

IV. CONCLUSION

A wideband digitally programmable RF feed network operating in the range form 2.5 to 6 GHz was designed and fabricated. The fabricated board had a total size of $111 \times 63 \times 0.8$ mm^3 and was fabricated on a commercial FR-4 substrate. This is a standalone design that can be applied to any type of antenna array or multi-path RF system. The results showed measured amplitude resolution of 0.5 with 0.22 dB maximum deviation and phase resolutions of 5.6° with 1° maximum deviation.

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