Retrodirective Transceiver Utilizing Phased Array and Direction Finder

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Abstract **─** Retrodirectivity have several important applications in communication and in wireless power transfer. In this paper, frequency sensitive retrodirective transceiver is proposed. It receives a signal and infers its direction from its frequency spectrum, then it can transmit a new signal back to the same or other direction at the designer wish. To determine the direction of the coming signal, a 0.85-1.15GHz frequency scanning phased array antenna is used so that the received signal would have a distorted spectrum with the maximum amplitude frequency component linked to the direction of the signal. Based on the frequency scanning, the retrodirectivity system can be used for wireless power transfer or for reactive jamming. Special circuit is designed to receive the signal with strongest power and to isolate the frequency component with maximum amplitude. Phase-locked loop (PLL) circuit is used to link such frequency to specific phase shift that is introduced to the transmitter array antenna to send a new signal to the same direction of the received signal. ADS simulation is performed to demonstrate the performance of each block.

***Index Terms*─** Frequency component isolation circuit, frequency scanning antenna array, retrodirective antenna.

I. INTRODUCTION

The Retrodirectivity refers to the process of retransmitting a signal to the same direction it arrived from without knowing its direction in advance [1]. It has many advantages like reducing the interference with other signals in addition to reducing power demand since the transmission will be in single direction. The two most common methods used to implement retrodirectivity are Van Atta array and phase conjugate methods.

Van Atta array method [2] works by interconnecting receivers and transmitters in a way that makes the last receiving element in phase with the first transmitting element. Doing this ensures the signal will be transmitted back to the same destination it came from. Several variations have been done to improve the performance of the array but they share the same principle [3-4]. Phase conjugate method [1] operates by introducing a phase shift at each receiving element which makes them out of phase with the transmitting elements, hence, transmitting the signal in the same direction of reception. There are multiple variations on the method as well, they use the same principle with different methods to introduce the phase shift [5-7].

The main shortcoming of both methods, however, is that they retransmit the signal with the same frequency it arrives with making them inflexible towards changing the content and the nature of the signal to be retransmitted. Frequency scanning phase array is an antenna whose radiation pattern changes with frequency. Recently, there have been multiple publications that uses this concept for different applications [8-10].

In this work, a new method for retrodirectivity that utilizes frequency scanning is proposed. The method separates the receiving and transmitting units which give the transmitter the freedom to send any signal back to same direction or for that matter to any other direction. Frequency scanning receiver receives specific frequency optimally from specific direction making the optimally received frequency a signature that tells about the direction of the signal. The system have flexibility to be designed according to any specific bandwidth and that based on the operation principle required. So, in the transceiver circuit can be used to transmit any signal to a specific direction that is not known by the transmitter. For example, the circuit can be used for jamming a signal at unknown direction or it can be used to transmit a wireless power to a device at unknown direction [11].

II. TRANSCEIVER COMPONENTS

A. Receiving antenna array

In this work, a four element serially fed phased array antenna have been used as in (Fig. 1). It consists of four receivers connected serially by transmission lines.

At a fixed distance and azimuthal angle, the radiation pattern formula for such antenna is given by [12]:

$$S(\theta) = S_e(\theta) \left|\sum_{n=1}^{N} a_n \, e^{j\psi_n} \, e^{j\,(n-1)\,k\,d\cos(\theta)}\right|^2, \quad (1)$$

where,

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$S_e(\theta)$: Radiation pattern for single element.
a_n: Amplitude of the received signal at n[th] element.
ψ_n: Phase of n[th] element due to transmission line delay.
k: Wave number $(\frac{2\pi}{\lambda})$.
d: The interelement spacing.
θ: The angle from which the signal is received.
N: Number of antennas.

If the transmission lines are designed to have integer multiples of 2π (zero) phase shift at the center frequency (i.e., 1 GHz), ψ_n will relate to frequency as follows:

$$\psi_n = 2\pi\, n\, m\, \frac{\lambda_0}{\lambda}\,, \tag{2}$$

where λ_0 is the wavelength at center frequency (1GHz), λ is the wavelength at the frequency under consideration and n is introduced because there are n transmission lines connecting n[th] antenna to the port. m is an integer above 1 for the designer choice to control the phase change sensitivity when frequency changes. Moreover, if the interelement spacing is chosen to be half wavelength at center frequency, its multiplication with wave number will be:

$$\boldsymbol{k\, d} = \frac{2\pi}{\lambda} * \frac{\lambda_0}{2} = \frac{\lambda_0}{\lambda}\,\boldsymbol{\pi}. \tag{3}$$

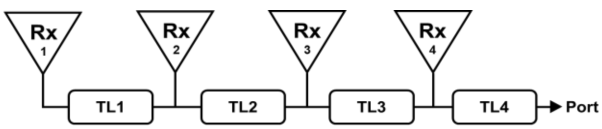

Fig. 1. Serially fed array antenna along with the transmission lines.

With the previous relations, (1) can be written as:

$$S(N,\lambda,m,\theta) = S_e(\theta)\,\left|e^{-j\frac{\lambda_0}{\lambda}\pi\cos(\theta)}\right|^2$$
$$\times \left|\sum_{n=1}^{N} a_n\, e^{j\,2\pi\, n\, m\frac{\lambda_0}{\lambda}}\ e^{j\,n\,\frac{\lambda_0}{\lambda}\pi\cos(\theta)}\right|^2. \tag{4}$$

In this design we assumed using an omnidirectional antenna. However, any antenna who has a half power beam width more than the scanning range of the antenna can be used. If omnidirectional individual antennas (i.e., having a radiation pattern independent of θ) are chosen, $S_e(\theta)$term can be ignored because only the normalized pattern is of concern. The same is true for any magnitude of phase term (i.e., $|e^{-jx}|$) which leads to:

$$S(\gamma) = \left|\sum_{n=1}^{N} a_n\, e^{jn\gamma}\ \right|^2, \tag{5}$$

where,

$$\gamma = \pi\,\frac{\lambda_0}{\lambda}\,(2m + \cos\theta) = \pi\,\frac{f}{f_0}\,(2m+\cos\theta). \tag{6}$$

Since the signal is received from a far distance, all a_ns are the same and equal unity. Having this in mind, (5) becomes a well-known sum that can be simplified to [12]:

$$S(\gamma) = \frac{\sin\left(\frac{N\gamma}{2}\right)^2}{\sin\left(\frac{\gamma}{2}\right)^2}\,. \tag{7}$$

Using (6) to substitute for γ, the closed-form formula for radiation pattern becomes:

$$S(N,f,m,\theta) = \frac{\sin\left(\frac{N}{2}(\pi\frac{f}{f_0}(2m+\cos\theta))\right)^2}{\sin\left(\frac{1}{2}(\pi\frac{f}{f_0}(2m+\cos\theta))\right)^2}\,. \tag{8}$$

Using MATLAB, the relation in (8) versus θ is plotted at different frequencies (Fig. 2).

As can be seen from the radiation pattern, each frequency has a ‘preferable’ direction at which it is optimally received. Therefore, if a signal that has uniform frequency spectrum within 0.85-1.15 GHz is sent, the frequency spectrum of the signal after it is received will be distorted. Depending on the direction of the signal, some frequencies will be received better than others. Figure 3 shows the frequency spectrum of a uniform signal after reception from different angles. The plot is generated from (8) after fixing N to 4 and m to 2.

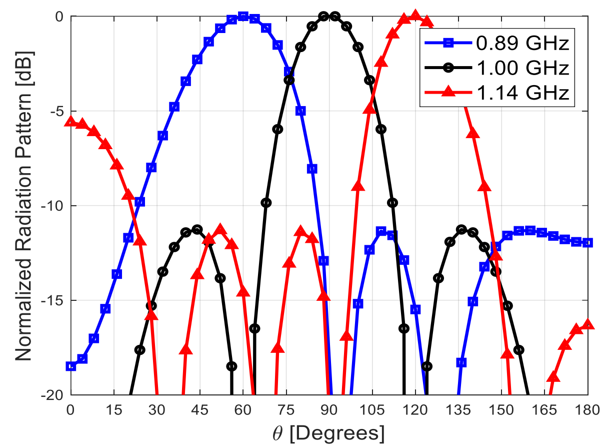

Fig. 2. Normalized pattern Vs θ at different frequencies (N=4, m=2).

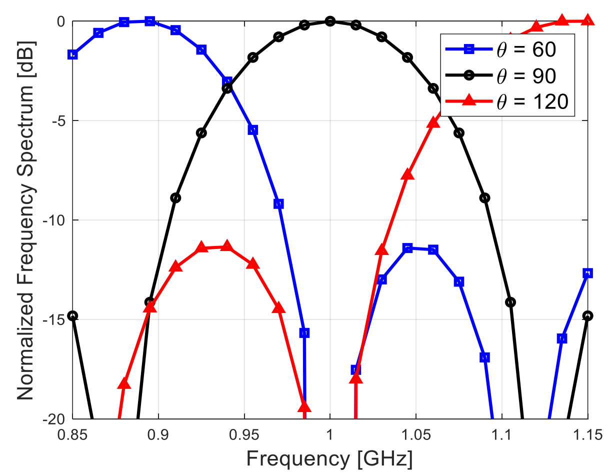

Fig. 3. Frequency spectrum of a uniform signal after reception.

B. Frequency component isolation circuit

The goal of this circuit is to take the signal with distorted spectrum and isolate the frequency component that has the maximum amplitude so that the signal direction is determined. Towards that end the circuit performs four operations which are down conversion, frequency sampling, filtering and comparison.

Down conversion is done to simplify the electronics needed to perform the other operations. After that comes the frequency sampling operation which is essential to make the filters - in the later stage - able to extract single frequency components from continuous spectrum. Mathematically, the signal out of the mixer will be:

$$m(t) = m_{Received}(t) * \cos(2\pi f_c\, t). \qquad (9)$$

If the signal $m(t)$ is repeated and delayed by constant T_0:

$$g(t) = \sum_{n=-\infty}^{+\infty} m(t - nT_0). \qquad (10)$$

Its Fourier transform will be the following [13]:

$$G(2\pi f) = \sum_{n=-\infty}^{+\infty} \frac{2\pi}{T_0} M\left(n\frac{2\pi}{T_0}\right) \delta\left(2\pi f - n\frac{2\pi}{T_0}\right). \qquad (11)$$

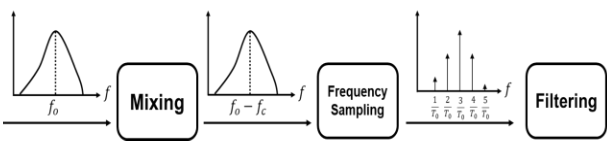

Fig. 4. Block diagram illustration of mixing and sampling.

Where the capital letters refer to the Fourier transform of the respected functions and $\delta(*)$ is the Dirac delta function. As can be seen, the transform is a set of samples in frequency domain and their separation can be controlled by adjusting T_0. Therefore, a basic delay loop can be used to repeat the signal in time domain which corresponds to sampling in frequency domain. Figure 4 illustrates the mixing and sampling operations in block diagram. It should be noted that the closer the samples to each other, the more accurate the direction estimation is at the expanse of high requirements for filters to isolate the very closely sampled frequency components. After sampling in frequency, filtering and comparison are required in order to determine the frequency sample with highest amplitude. This is especially important for the later stage in which Phased-locked-loop (PLL) is used to convert the frequency into a DC voltage to be used in transmitter's phase shifters. PLL cannot lock on signals with multiple frequency components, hence the need to eliminate all components but the one with highest amplitude. If the scene is divided into N (even) directions (angles), N bandpass filters are required for filtering so that the frequency component corresponding to each direction get isolated in order to be compared to the rest.

In comparison operation, the output of each filter branches out into two branches where one branch gets rectified and the other branch is connected to a voltage-controlled (VC) switch. The rectified signals get compared by a comparator and the output of the comparator is connected to the VC switches so that only the component with higher amplitude passes. The comparison operation is done in multiple stages with each stage reducing half of the components, the last stage results in a single surviving component that indicates the direction of the received signal. Figure 5 shows block diagram illustration of the filtering and comparison.

The last part of the circuit is a PLL that converts the surviving frequency component to a DC voltage (at the input of the VCO inside the PLL) that is used by the phase shifters in the transmitting antenna array.

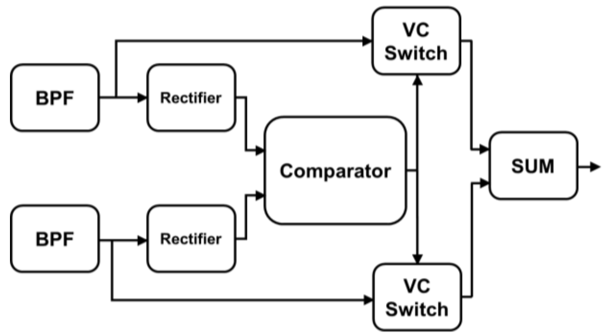

Fig. 5. Filtering and comparison part for two frequency components.

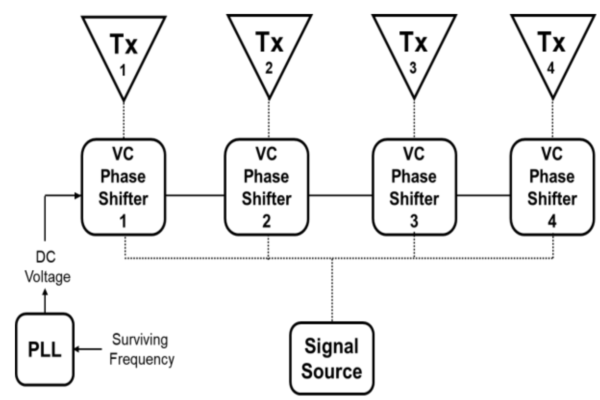

Fig. 6. Transmitting antenna array.

C. Transmitting antenna array

The array consists of four elements connected in parallel with each element preceded by VC phase shifter as in Fig. 6. The phase shifters are designed to give the following phase:

$$\psi_{Tx(n)} = 2\pi\, n\, r\, DC\_Voltage, \qquad (12)$$

where n is the antenna's number and r is a design parameter. r is chosen in such a way that (12) equals negative of (2) which leads to transmission in the same direction of reception, it also can be chosen to make the antenna radiates in opposite direction or any direction in between at the designer wish. Furthermore, it should be noted the transmitted signal source is independent of the received signal adding more freedom to the transceiver compared to other retrodirectivity methods.

III. SIMULATION RESULTS AND DISCUSSION

A. Receiving antenna array results

To verify the mathematical analysis that led to (8), Harmonic Balance (HB) simulation in ADS software was used. Utilizing Principle of Reciprocity, the receiving antenna was modelled as transmitting antenna. The network has 5 terminals, one is the feeding port and the other four represent antennas and they are serially connected by microstrip transmission lines each of electrical length 4π - corresponding to m=2 in (2). The spatial delay ($e^{jnkd\cos(\theta)}$) was modelled by ideal transmission line. Figure 7 shows the ADC circuit used in the simulation. A non-ideal transmission line is used to connect the antenna elements. These line are TL1, TL2, TL3, and TL4. There is a very good agreement between the results obtained by ADS simulation and the theoretical relation derived above which confirms the validity of the derivation. The results in Figs. 8 and 9 are from ADS based on a non-ideal transmission line to include the effect of the dispersion and the group delay.

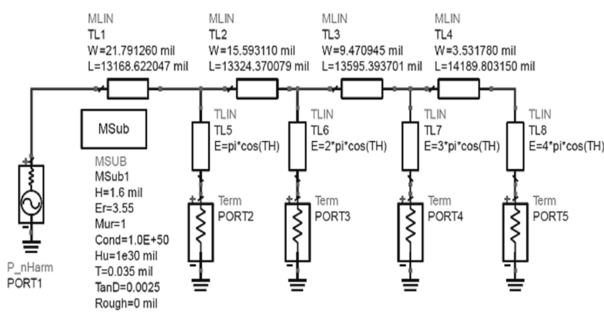

Fig. 7. ADS circuit for receiver.

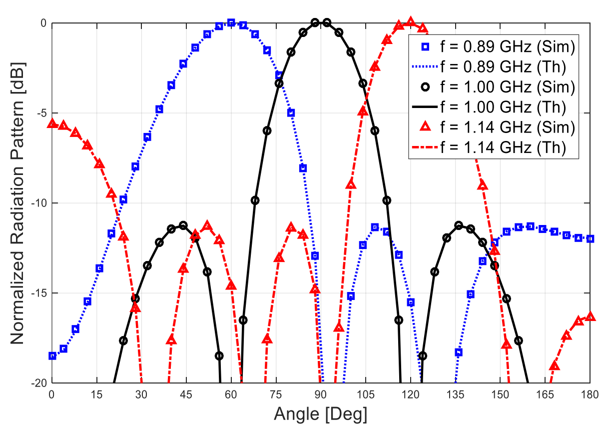

Fig. 8. Simulation results at different frequencies.

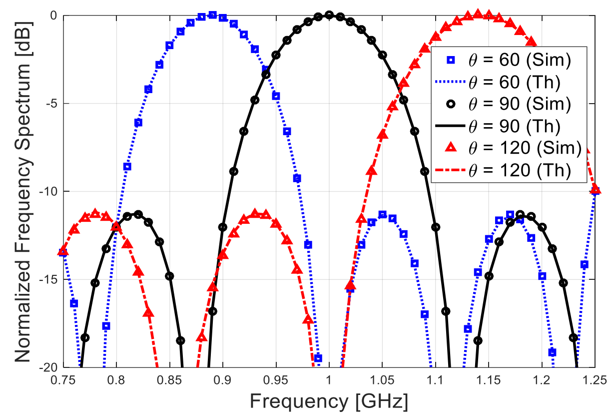

Fig. 9. Reception frequency spectrum at different angles.

B. Frequency component isolation circuit results

To demonstrate the circuit performance, a signal peaked at 0.89 GHz like the one in (Fig. 9) is inputted to the circuit. Figure 10 and Fig. 11 show the ADS circuit used for mixing and sampling and the simulation results respectively. The scan range is directly proportional to the bandwidth and the beam width of the antenna. This circuit can work at scan angle 18^0o or 0^0.

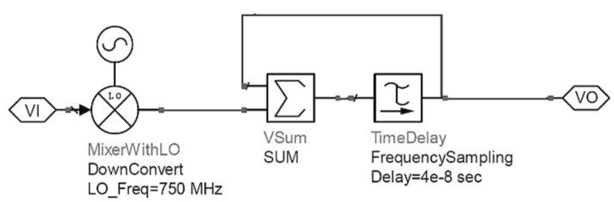

Fig. 10. ADS circuit for mixing and frequency sampling.

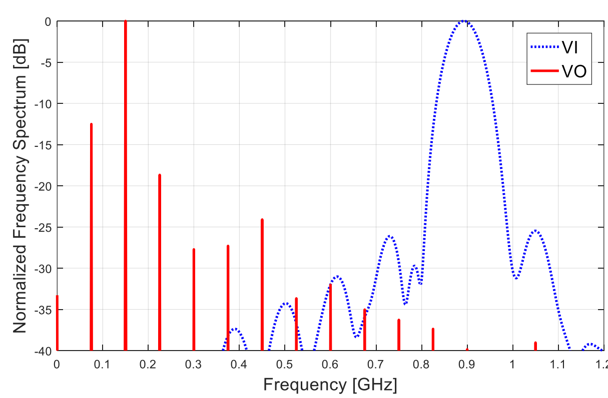

Fig. 11. ADS simulation results for mixing and frequency sampling.

After the down conversion and sampling comes filtering and comparison. For simplicity, the simulation is done for two frequency components only (i.e., 75 and 150 MHz) but the same block can be used again and again to filter all components and isolate the one with highest amplitude. The ADS circuit used to build the block is shown in (Fig. 12) and the HB simulation results are shown in (Fig. 13). All other components were suppressed except the one with highest amplitude.

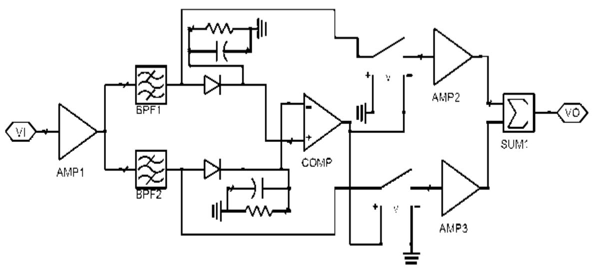

Fig. 12. ADS circuit for filtering and comparison block for two frequency components.

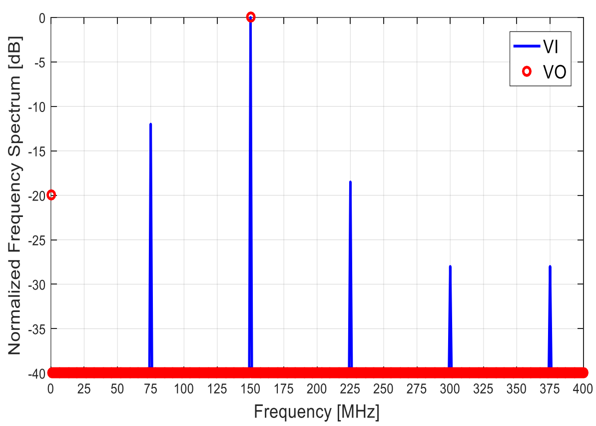

Fig. 13. ADS simulation results for filtering and comparison block.

Having the harmonic with highest amplitude isolated from the rest, it needs to be converted to a frequency proportional DC voltage. This is done by taking the input signal of VCO in PLL circuit. Figure 14 and (Fig. 15) show the PLL circuit in ADS and the PLL characteristics (i.e., DC vs frequency) respectively.

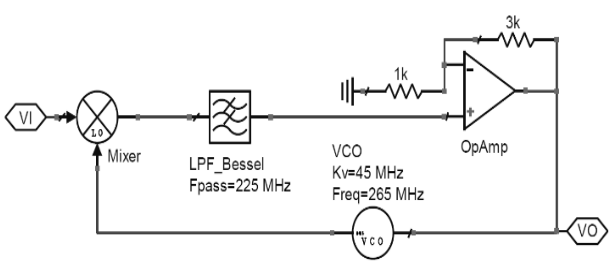

Fig. 14. ADS circuit PLL.

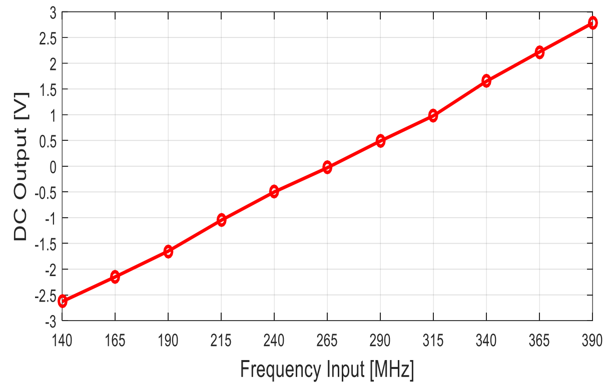

Fig. 15. PLL characteristics.

C. Transmitting antenna array results

The DC voltage is feed to set of DC varactor-based reflection phase shifters [14] that have phase characteristics (phase vs DC) similar to transmission lines characteristics (phase vs frequency) with the DC linked to frequency by PLL curve in (Fig. 15). Figure 16 shows the ADS circuit for phase shifter while (Fig. 17) shows its characteristics.

Based on the characteristics, connecting two phase shifters in series is equivalent to one transmission line phase shift in (2). Therefore, for the first antenna we need two phase shifters and the second we need four and so on. Having the phase shifters designed and tuned, the transmitter circuit is constructed in ADS as in (Fig. 18) it should be noted that the source at the port is independent of the received signal.

Using such circuit, HB simulation was performed at 1GHz (the transmitted signal frequency). The resulting transmission radiation pattern as compared to the reception radiation pattern is shown in (Fig. 19).

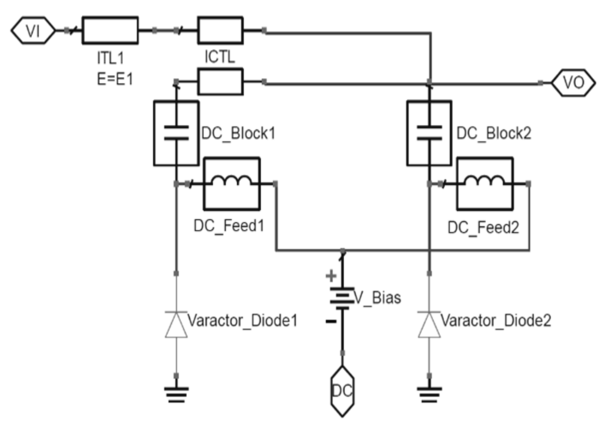

Fig. 16. ADS circuit for one phase shifter. V_Bias and E1 (electrical length) are used to control the characteristics of the phase shift.

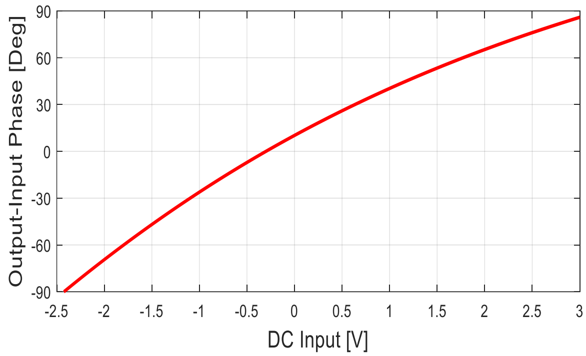

Fig. 17. Characteristics of two phase shifters connected in series.

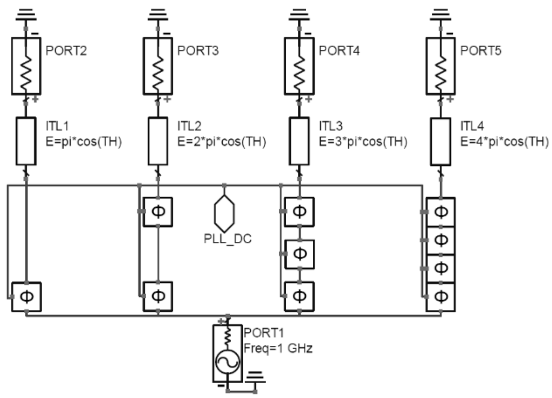

Fig. 18. ADS circuit for transmitter.

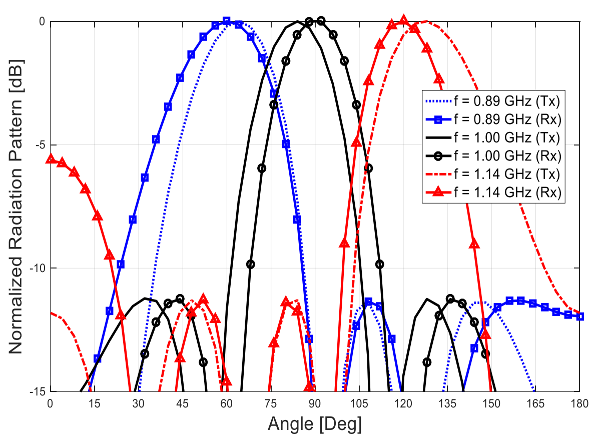

Fig. 19. Transmission (not marked) and reception (marked) radiation patterns for different directions (frequencies) of the received signal.

VI. CONCLUSION

In this paper, a new method for retrodirectivity that utilizes frequency scanning phase array antenna was presented. In detail conceptual explanation for each part of the transceiver was provided. The method was verified using ADS simulation for each part of the transceiver. The system have the ability to transmit the signal to any location other than the direction of arrival and to transmit a signal has different waveforms than the received one and have flexibility to be designed according to any specific bandwidth and that based on the operation principle required.

Future work can be made more comprehensive by using two antennas for reception, one omnidirectional antenna and one frequency scanning antenna. Dividing the two received signals from these antennas will produce a reception frequency spectrum as if the transmitted signal was uniform in frequency. This will make the system work irrespective of frequency spectrum uniformity of the received signal.

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