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Frequency Scanning Antenna Arrays with Pentagonal Dipoles of Different Impedances

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Abstract: In this work we present the benefits of using pentagonal dipoles as radiating elements instead of classical printed dipoles in the design of frequency scanning antenna arrays. We investigate how impedance of pentagonal dipoles, which can be changed in a wide range, influences the overall characteristics of the uniform antenna array. Some very important antenna characteristics such as side lobe level, gain and scanning angle are compared for three different antenna arrays consisting of identical pentagonal dipoles with impedances of 500 Ω, 1000 Ω and 1500 Ω.

Keywords: Antenna array, Frequency scanning, Pentagonal dipoles, Phase shifter, Split-ring resonator.

1 Introduction

Scanning antennas are a very important antenna class, whose main radiation beam can be moved in different spatial directions. Earliest designs of these antennas related to mechanical scanning antennas which were fixed at rotating docks. Their performances are determined by the efficiency of the mechanical parts and problems such as inertia, time lags and vibrations [1], so dealing with multiple targets was quite difficult. Nowadays mechanical scanning antennas are mostly used for the specific radar applications operating with very high powers.

Later developed and prevalent type of scanning antennas are phased arrays [2]. Theoretical principle of phased arrays is based on the constructive and destructive interference, stating that electromagnetic energy received at a specific point in space from two or more closely spaced radiating elements is at maximum when the energy from each radiating element arrives in phase at that point. The signal will be amplified by constructive interference in the main direction and the beam sharpness is improved by means of destructive interference. Direction of the main beam depends directly on the phase shift between the radiating elements. There are different phase shifters which can be employed for accomplishing the phase shift in scanning antennas. Electronically

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controlled phase shifters are usually composed of numerous switchable detour lines, allowing the selection of a specific phase shift from the group of available values enabling scanning only at specific positions corresponding to a given phase shift. Constant phase shift $\Delta\phi$ between two successive radiating elements is called phase-increment. If d is a distance between the radiating elements designed to work at wavelength λ, than beam steering from normal broadside direction Θ_s, can be calculated according to [1]:

$$\Theta_s = \arcsin \frac{\Delta\phi}{360^\circ} \frac{\lambda}{d} . \quad (1)$$

Advantages of phase scanning is high gain and low side lobes, multi-target handling within microseconds and multifunction operation by emitting several beams simultaneously. Also phase scanning is resistant to single component faults that reduces the beam sharpness, but the system remains operational.

Frequency scanning antennas are a special case of phased arrays. They use frequency dependent phase shifters therefore enabling the positioning of the main beam at any given direction within the operating frequency range of the antenna. The beam steering is a function of the transmitted frequency and requires certain frequency bandwidth, which can be a problem due to limited available frequency band. Therefore, the main requirement in the design of frequency scanning antennas is to ensure the largest possible scanning angle for a very small change of frequency, i.e. a high frequency sensitivity.

Printed frequency scanning antenna fed at the center frequency of 6 GHz using $2\lambda_g$ long meander balanced microstrip between dipoles is shown in [3]. The antenna array exhibits a wide scanning range of about 50°, but requires relative frequency variation of 20%, due to slow change of phase with frequency in the transmission line. Similar approach using low loss transmission line for the phase shifting is presented in [4]. Antenna is realized on a 3-layer substrate and exhibits a wider beam scanning angle of 73° with rather poor frequency sensitivity of 43.24°/GHz. Frequency scanning antenna with significantly improved frequency sensitivity of 1.64°/MHz is shown in [5]. It exploits band-pass filters between radiating antenna elements to provide additional phase shift. The main drawback of this approach is a pretty high insertion loss in feeding network that considerably reduces the antenna gain. Hence, the proposed scanning antenna consisting of 11 radiating elements exhibits gain of only –6 dBi.

In this paper we present linear frequency scanning antenna arrays consisting of identical pentagonal dipoles with different impedances. Frequency scanning is achieved using identical phase shifters consisting of split-ring resonators placed between pentagonal dipoles. We investigate how impedance of pentagonal dipoles, which can be changed in a wide range, influences the overall characteristics of a uniform scanning antenna array.

2 Antenna Array

2.1 Design considerations

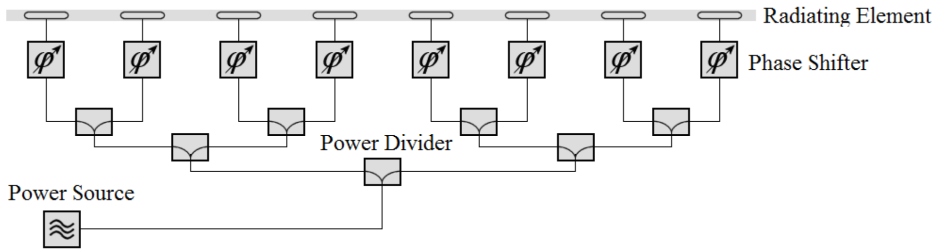
In this work we present a frequency scanning antenna array with pentagonal dipoles as radiating elements. Pentagonal dipoles are implemented in microstrip technology, with the use of balanced microstrip line. This type of dipole does not have the problems associated with the patch antenna in terms of a very narrow bandwidth and may be implemented in various forms depending on the specific needs. Reason for using the pentagonal dipoles as radiating elements is theirs ability to cover an extremely large range of impedances. Typical impedance values of radiating elements in the array are between 200 Ω and 400 Ω. Radiating elements with higher impedances are rarely used since they require very narrow microstrip lines which are difficult to fabricate. In the design of the antenna arrays impedance of the radiating elements is very important, since it determines which amount of available power will be radiated, so in that manner it can be used for power distribution in the array. This is especially the case with the linear scanning antennas.

Linear scanning antenna is designed with series feeding network (Fig. 1b) that has some important advantages over the corporate feed in Fig. 1a.

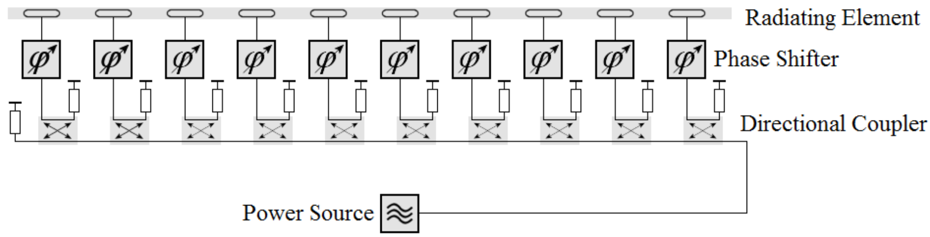
In the case of corporate feed each radiating element has a direct link to the source through the feeding network which is usually comprised of numerous T-junctions or Wilkinson power dividers and impedance transformers [6]. Using corporate feed it is very easy to achieve any power distribution in the array. But, for the scanning antennas corporate feed can be quite an expensive solution. As stated before, in order to have scanning the relative phase shift between radiating elements should be equal, which means that the N elements of the array requires n_c phase shifters:

$$n_c = \sum_{i=2}^{N} (i-1)\,. \tag{2}$$

Resulting network can be quite large and very expensive. On the other hand, series feeding network is usually quite simple and therefore a typical choice for the linear scanning antennas. In this case the array of N elements requires N-1 phase shifters. Phase shifter is placed between each radiating element and thus enabling equal relative phase shift. On the other hand power distribution in series feed array is harder to obtain due to the fact that typically only the first element has a direct link to the power source and each consecutive element has only a portion of that power at disposal. Impedance of the radiating elements and losses in shifters determine the overall power distribution.



(a)



(b)

Fig. 1 – *Feeds of the antenna array:* (a) *Corporate feed;* (b) *Series feed.*

2.2 Phase shifter design

As a phase shifter we use the structure designed with a single left-handed unit cell which consists of four split-ring resonators (SRRs) coupled with the balanced microstrip line and a metal via connecting top and bottom strip of the balanced line, as it is shown in Fig. 2.

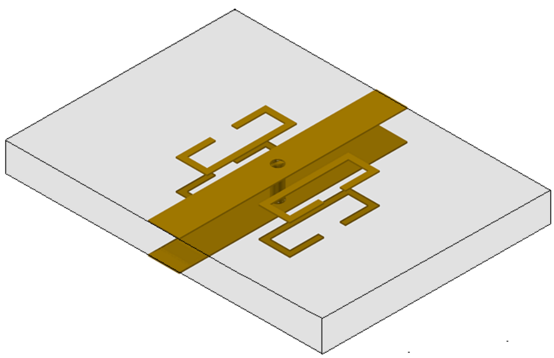


Fig. 2 – *Layout of the phased shifter with four elongated split-ring resonators.*

The shifter is designed on RT/duroid 5880 substrate with thickness of 0.508 mm. Impedance of the balanced microstrip line is 100 Ω and its length is 0.5 λ_0 i.e. 15 mm at 10 GHz. Two SRRs are placed at the top side of the substrate, while the other two are on the bottom side. In order to achieve the desired *S*-parameters, we modified commonly used square SRR by elongating them along the balanced microstrip line in order to increase the coupling between the SRR and the balanced line. Dimension of SRRs are obtained through the optimization with WIPL-D Pro [7], full-wave electromagnetic solver based on the method of moments. Characteristics of the SRRs based phase shifter are given in Fig 3.

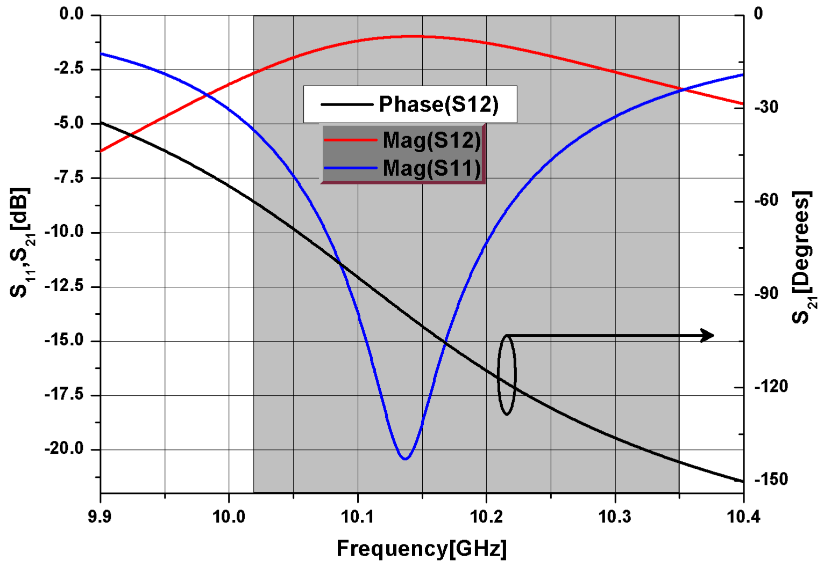


Fig. 3 – *S-parameters of the phase shifter.*

SRR shifter exhibits band-pass filter characteristics, due to the presence of SRRs and via, as can be seen in Fig. 3. Due to almost linear phase characteristics of S_{21}, SRR shifter provides almost linear change of the scanning angle as a function of frequency. Frequency bandwidth of interest is from 10.02 GHz to 10.35 GHz, where we can see the maximum value of S_{21} of –0.95 dB, the average value of –1.5 dB, and the minimum value of S_{11} –21 dB.

Similar antenna array design using this type of shifter is also applied in [8], but with the classical dipoles operating at 6 GHz. Scanning antenna using different pentagonal dipoles operating at 10 GHz is presented in [9]. Side lobe suppression better than 18 dB for the beam scanning of 30 degrees is achieved.

2.3 Antenna array design

Antenna is designed as a linear scanning array with eight identical pentagonal dipoles and a phase shifter placed between them (Fig. 4). One half of the dipoles are printed on one side of substrate and the other half on the other side. Distance between the dipoles in the array is 0.5 λ_0, where λ_0 is the freespace wavelength. The antenna array is positioned above the reflector plane at a distance of a quarter wavelength in the air. Transition from balanced to unbalanced microstrip line is achieved using continuous (taper) balun at the power source side omitted in Fig. 4). Layouts of the dipoles for different impedance values are given in Fig. 5.

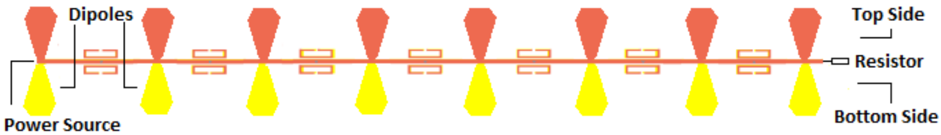


Fig. 4 – *Layout of the antenna array.*

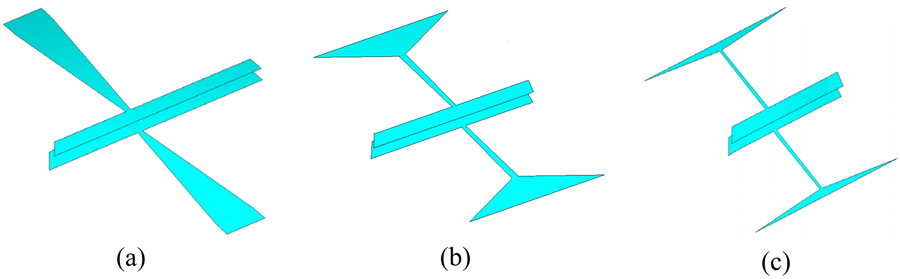


Fig. 5 – *Layout of the dipole connected to the balanced microstrip line with impedance:* (a) 500 Ω; (b) 1000 Ω; (c) 1500 Ω.

Power source at the beginning of the array (Fig. 4) excites the dipoles which radiate part of the power while significant part of it is attenuated due to losses in shifters. Resistor of 100 Ω is placed at the end of the array to prevent power reflection from the end of the array. Without the resistor, the array would act as it were excited with two power sources which would increase the side lobes due to opposite flow of energy. In order to control power distribution in the array we use radiating elements with different impedances. In Figs. 6-8 we show the radiating patterns of the antennas comprised of pentagonal dipoles with impedances of 500 Ω, 1000 Ω and 1500 Ω.

It can be seen that antenna beam scanning occurs from 100° to 136° for a frequency variation of 330 MHz and it does not depend on the dipole impedance, but on the phase shifter. From **Table 1** and **Table 2** we can see that only regarding the gain the array with radiating elements of 500 Ω is slightly better, but considering the other characteristics, such as side lobe level and 3dB beamwidth, array with 1000 Ω radiating elements is better and the one with 1500 Ω is the best. The main reason for this is the better power distribution gained by using the elements with higher impedance. In that case each radiating element will take a smaller portion of the available power, giving the successive elements more power to use. The advantage of using high impedance dipoles in the arrays with series feeding will be more pronounced in arrays with greater number of elements.

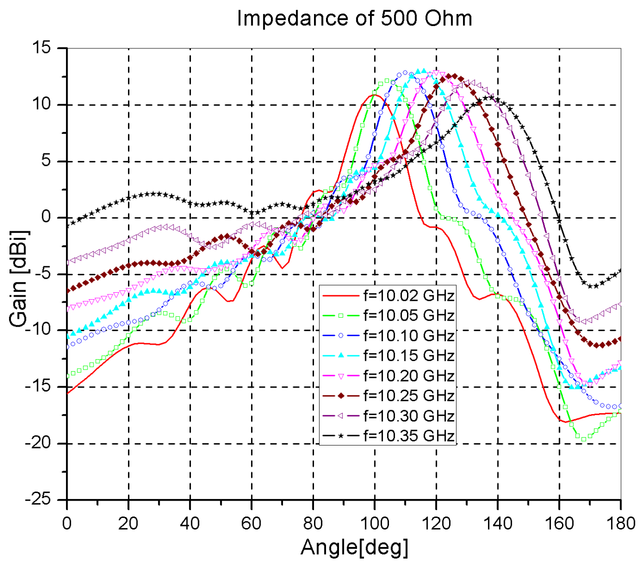


Fig. 6 – *Radiation pattern for the array with pentagonal dipoles of* 500 Ω.

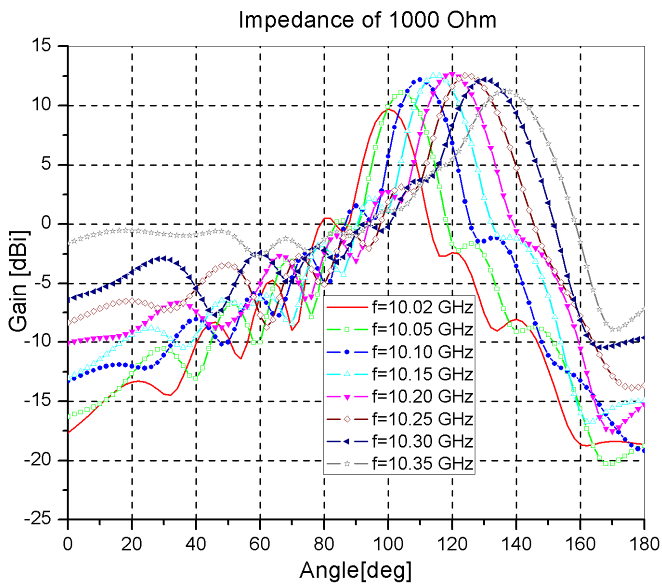


Fig. 7 – *Radiation pattern for the array with pentagonal dipoles of* 1000 Ω.

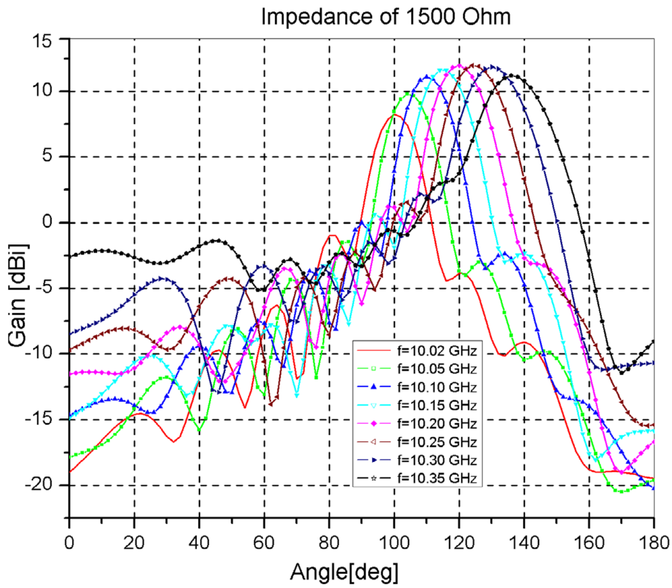


Fig. 8 – *Radiation pattern for the array with pentagonal dipoles of* 1500 Ω.

Table 1

Comparison of gain and side lobe level (SLL for different dipole impedances).

	Gain[dBi]			SLL[dB]		
Frequency[GHz]	500 Ω	1000 Ω	1500 Ω	500 Ω	1000 Ω	1500 Ω
10.02	10.9	9.7	8.2	8.5	9.2	9.2
10.05	12.2	11.1	9.8	9.5	10.9	11.3
10.10	12.9	12.2	11.1	9.3	10.7	11.1
10.15	13.0	12.6	11.6	8.7	10.4	11.0
10.20	12.9	12.7	12.0	8.1	9.9	10.7
10.25	12.6	12.5	12.0	7.4	9.4	10.4
10.30	12.0	12.2	11.9	6.5	8.5	9.7
10.35	10.6	11.2	11.2	6.3	7.0	8.2

Table 2
3dB- beamwidth comparison.

	3dB beamwidth[°]		
Frequency[GHz]	500 Ω	1000 Ω	1500 Ω
10.02	14.4	14.0	13.4
10.05	14.7	14.1	13.8
10.10	15.4	14.1	14.0
10.15	16.4	15.4	14.8
10.20	17.3	16.0	15.6
10.25	19.0	17.3	16.7
10.30	21.4	19.1	18.2
10.35	25.1	22.5	20.3

3 Conclusion

In this paper we compared the characteristics of three linear frequency scanning antenna arrays designed with identical pentagonal dipoles having different impedances: 500 Ω, 1000 Ω and 1500 Ω. It was shown that arrays with high impedance dipoles exhibit lower side lobes and narrower 3 dB beamwidth with respect to arrays comprised of low impedance dipoles. The main reason for this is the series feeding of the array in which the successive radiating elements take smaller portions of the available power. Pentagonal dipoles are very suitable for the design of series arrays since their impedances can cover the range from 80 Ω to over 1600 Ω.

4 Acknowledgment

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