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Octave-Band Four-Beam Antenna Arrays with Stable Beam Direction Fed by Broadband 4×4 Butler Matrix

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Abstract: A novel concept of four-beam antenna arrays operating in a one-octave frequency range that allows stable beam directions and beamwidths to be achieved is proposed. As shown, such radiation patterns can be obtained when radiating elements are appropriately spaced and fed by a broadband 4×4 Butler matrix with directional filters connected to its outputs. In this solution, broadband radiating elements are arranged in such a way that, for the lower and upper frequencies, two separate subarrays can be distinguished, each one consisting of identically arranged radiating elements. The subarrays are fed by a broadband Butler matrix at the output to which an appropriate feeding network based on directional filters is connected. These filters ensure smooth signal switching across the operational bandwidth between elements utilized at lower and higher frequency bands. Therefore, as shown, it is possible to control both beamwidths and beam directions of the resulting multi-beam antenna arrays. Moreover, two different concepts of the feeding network connected in between the Butler matrix and radiating elements for lowering the sidelobes are discussed. The theoretical analyses of the proposed antenna arrays are shown and confirmed by measurements of the developed two-antenna arrays consisting of eight and twelve radiating elements, operating in a 2–4 GHz frequency range.

Keywords: antenna feeds; beam steering; Butler matrix; microstrip antennas; scalability



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1. Introduction

In recent years, the development of modern wireless systems caused interest in advanced antenna technology, among which multibeam antennas that offer multiple independent beams can be distinguished. The concept of multibeam antennas was introduced by Shelton [1] and has become the subject of extensive research up to date [2–4]. Multibeam antenna arrays can be realized with the use of beamforming networks, such as Butler matrices, which ensure an appropriate signal distribution across the array [5]. Although there are many reported solutions that involve Butler matrices realized in different technologies, most of them are focused on narrowband concepts [6–9]. On the other hand, the constant development of communication systems calls for more advanced solutions, such as multiband or broadband networks. Therefore, the concept of scalable antenna arrays has recently gained a lot of interest [10–16], since such arrays allow the assumed antenna parameters to be achieved, i.e., beamwidth or beam direction in a very broad bandwidth. In the literature, some concepts of scalable antenna arrays with constant broadside beam can be found [13,17,18] which are realized with the use of frequency-dependent feeding networks, whereas multi-beam antenna arrays with almost constant multiple beam patterns are rarely reported. This is due to the required distance between radiating elements which has to be kept around 0.5λ and appropriate signal distribution, which has to be ensured across the array in a broad bandwidth. Although broadband Butler matrices are known [19,20], the required spacing between radiating elements causes that dual-band concepts often involve separate antenna arrays operating in each sub-band [21,22], whereas

solutions that allow constant broad frequency range to be covered are rarely reported. One exemplary solution is described in [23], where multibeam antennas operating in an octave frequency range have been described. In this concept, frequency-dependent Butler matrices change their orders from N to $N/2$ as the frequency increases. As shown, multiple-beam radiation patterns can be achieved with such a beamforming network. As presented, even wider bandwidths can be achieved by the utilization of modified Butler matrices which change their behavior three times across the operational frequency range [24]. However, the major drawback of these solutions is the complexity of the applied beamforming networks, which limits the applicability of the described concepts [23,24]. A simpler approach to the realization of scalable multibeam antennas is presented in [25], where the feeding network consists of a broadband quadrature directional coupler and frequency-dependent power dividers. As shown, this allows an attractive two-beam radiation pattern to be achieved over the frequency range reaching $f_H/f_L = 3$. However, the solution proposed in [25] can be implemented only in two-beam antenna arrays and cannot be straightforwardly extended to antenna arrays with a higher number of beams.

In this paper, we present a novel concept of the multi-beam antenna arrays that allows a four-beam radiation pattern to be achieved over a one-octave frequency range. The proposed feeding network consists of a broadband Butler matrix at the outputs to which an appropriate feeding network based on directional filters is connected. Such a solution provides attractive four-beam radiation properties over a very broad bandwidth. Simultaneously, it leads to a simpler feeding network comparing to the previously developed concept [23], since the classic broadband Butler matrices are well developed and the required directional filters are relatively easy to design. The proposed concept was verified by the design and measurements of two four-beam antenna arrays operating in a 2–4 GHz frequency range and consisting of eight and twelve radiating elements, respectively.

2. Concept of Octave-Band Four-Beam Antenna Arrays

A concept of the proposed scalable four-beam antenna array is explained in Figure 1. It is based on [25]; however, there are substantial differences between these two approaches. First of all, the antenna array described in [25] utilizes four equally spaced broadband radiating elements. The distance between two inner elements at a higher frequency is equal to the one for two outer elements at a lower frequency; therefore, the frequency ratio in this case equals $f_H/f_L = 3$. This means that the concept described in [25] is only reserved for two-beam antenna arrays. Therefore, in this paper, we propose a novel approach, in which the radiating elements are not equally distributed across the array, as shown in Figure 1. In particular, the distance between the two elements operating at the lowest and highest frequencies (radiating elements marked in blue and red colors) is equal to half (or $3/2$ times) the distance between two inner elements (two middle radiating elements marked in red). This implies that the relative distance among all elements operating at a lower frequency is exactly the same as the one among the ones operating at a higher frequency when the frequency ratio is equal to $f_H/f_L = 2$. Such radiating elements' distribution allows scalable four-beam antenna arrays to be realized when appropriate modifications of the amplitude excitation are applied, as it is explained in detail below.

To generate a multiple beam radiation pattern, a broadband 4×4 Butler matrix together with four directional filters (DF) is utilized, as shown in Figure 1. The Butler matrix ensures appropriate amplitude and phase distribution between each pair of radiating elements that operate at high and low frequency ranges, whereas directional filters realize smooth signal switching between these elements. This implies that a similar radiation pattern can be obtained over the entire bandwidth from f_L to f_H (equal to $2f_L$). The proposed antenna array was analyzed with the use of numerical optimization and the frequency characteristics of the required directional filters were found. The optimization process focused on achieving the minimum beamwidth variation together with the minimum variation of all beams' directions. The resulting switching function is shown in Figure 2, which shows the amplitude delivered to each of the radiating elements operating at the

lowest frequency (marked as *LF*) together with the amplitude delivered to each radiating elements operating at the highest frequency range (marked as *HF*). As can be seen, the signal is smoothly switched between the lowest and highest frequency outputs of the directional filters across the bandwidth (see Figure 1). The optimization process reveals that, although it is possible to achieve an almost constant beam pattern across such a broad bandwidth, the relative sidelobe level reaches about -4 dB for such an array when the directivity of the single radiating element is taken into account. This is illustrated in Figure 3, where calculation results are shown assuming that the utilized radiating element is directive with its radiation pattern described by the approximate function $\cos^{1.3}(\theta)$. As can be seen, the two outer beams (2L and 2R beams) feature very low sidelobe levels reaching -4 dB. This is due to the fact that the angles at which the array factor has its maximum, the single radiating element features a severe attenuation; therefore, the relative sidelobe level raises.

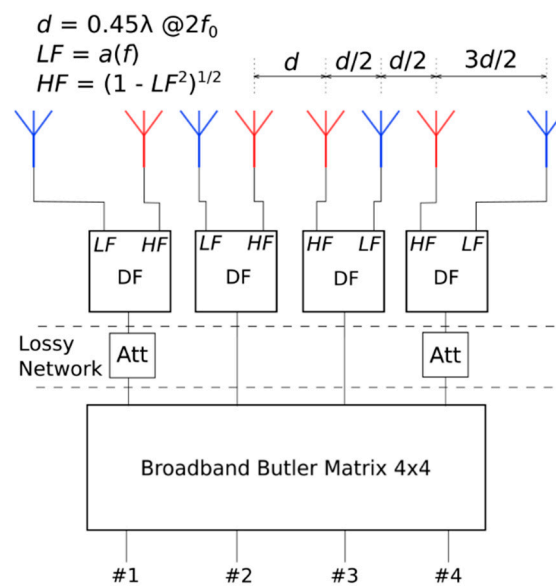


Figure 1. Concept of an octave-band four-beam antenna array composed of eight radiating elements and fed by a broadband 4×4 Butler matrix and directional filters. Red and blue colors denote subarrays operating at a higher (HF) and lower (LF) frequency, respectively.

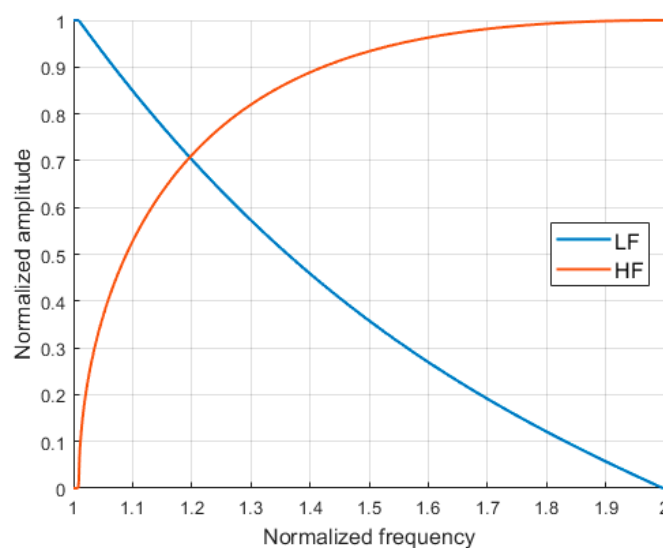


Figure 2. Normalized amplitudes delivered to appropriate outputs of directional filters feeding lower and higher frequency subarrays of the proposed broadband four-beam antenna array operating in an octave frequency range.

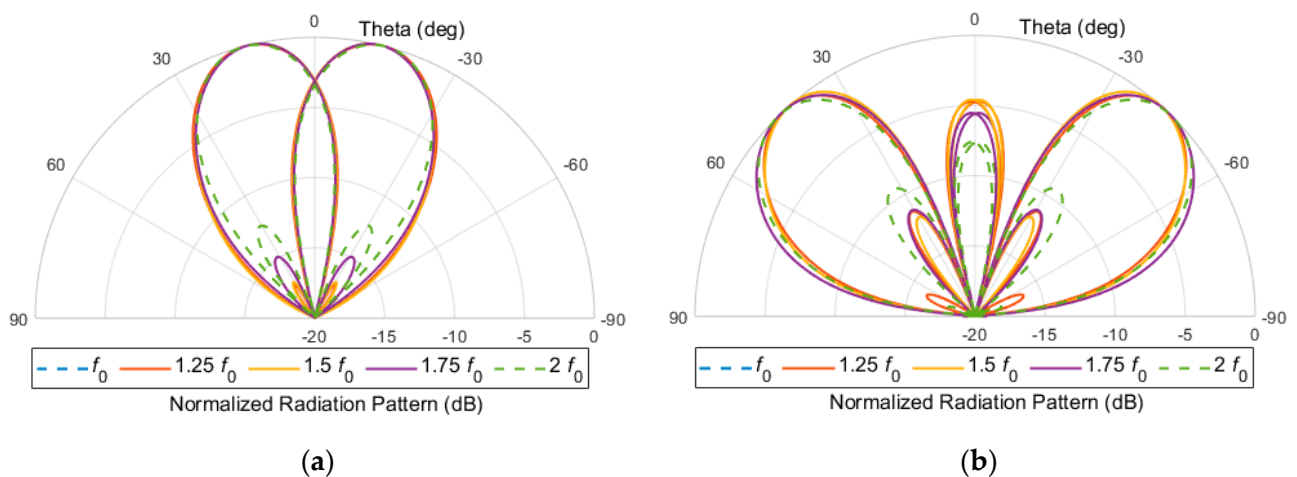


Figure 3. Calculated radiation pattern of scalable antenna array shown in Figure 1 in which a single radiating element having directive radiation pattern described by $\cos^{1.3}(\theta)$ was assumed and no attenuators are applied. (a) 1L and 1R beams and (b) 2L and 2R beams.

Therefore, in this paper, we propose the application of unequal power distribution to overcome this problem, which allows us to achieve a good radiation pattern. This is another substantial difference between this concept and the one presented in [25]. The tapered excitation across the proposed scalable antenna array can be achieved in either lossy or theoretically lossless networks. The first approach mentioned is illustrated in Figure 1, in which additional attenuators (Att) are applied in the outer channels between the applied Butler matrix and the four directional filters. By controlling the attenuation level of these two attenuators, it is possible to achieve tapered excitation across the entire antenna array. It has to be underlined that, by introducing only 1.25 dB of attenuation of the total signal resulted in the application of 3 dB attenuators in the outer channels, it is possible to improve the overall radiation pattern. The calculated radiation pattern is shown in Figure 4. As can be seen, the proposed method allows sidelobe level, which is now better than -10 dB, to be improved.

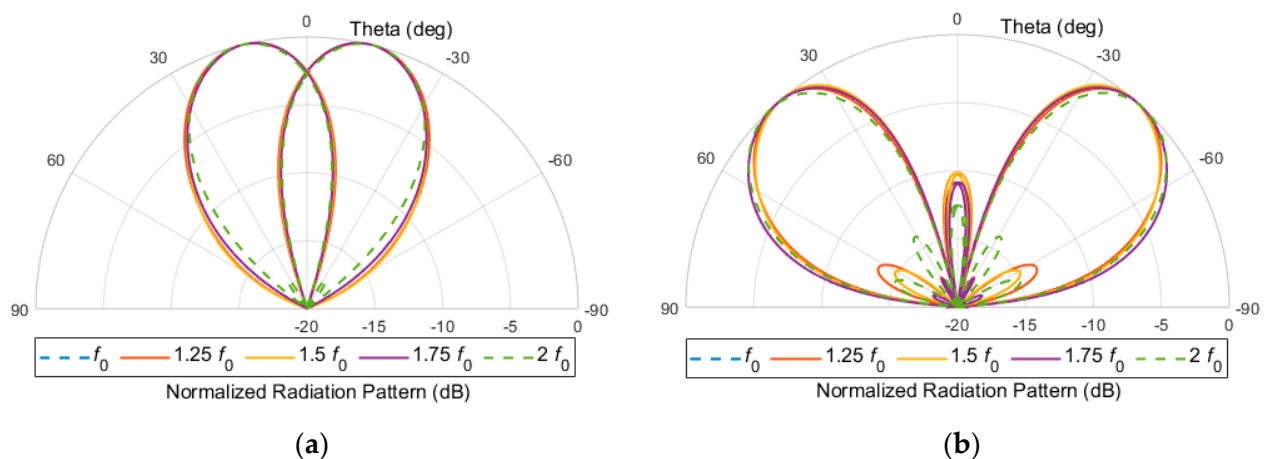


Figure 4. Calculated radiation pattern of scalable antenna array shown in Figure 1 in which additional 3 dB attenuators were applied in outer channels and a single radiating element having directive radiation pattern described by $\cos^{1.3}(\theta)$ was assumed. (a) 1L and 1R beams and (b) 2L and 2R beams.

The second possible approach which allows to minimize the sidelobe level of the resulting antenna array with a theoretically lossless network is based on the concept proposed in [6] and further developed in [7]. The schematic diagram of the proposed scalable antenna array is shown in Figure 5. As seen in this concept, twelve radiating elements are used to achieve taper excitation across the array and additional unequal power dividers having a power division ratio of 1:2.6 are applied, whereas, to achieve appropriate phase distributions, the selected four radiating elements are rotated, which ensures an ideal 180° phase shift. Moreover, the two outer elements operating at the lower frequency range marked in red color in Figure 5 are placed closer to reduce the directivity of the entire antenna array; therefore, they minimize the resulting grating lobe. Such modifications resulted in the scalable antenna array having the radiation pattern shown in Figure 6. As seen also in this case, a significant sidelobe reduction is achieved; however, the larger difference in beamwidths of the two outer beams that can be observed is caused by the high directivity of the entire antenna array, which is composed of twelve radiating elements.

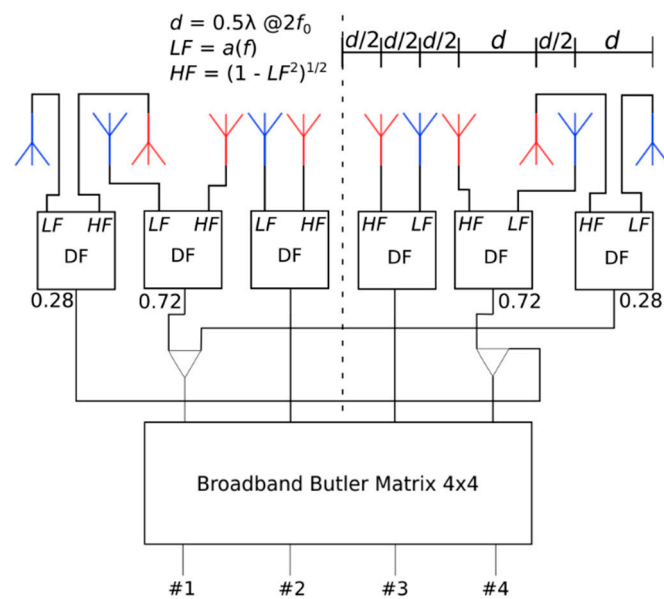


Figure 5. Concept of an octave-band four-beam antenna array composed of twelve radiating elements and fed by a broadband 4 × 4 Butler matrix, directional filters and additional power dividers. Red and blue colors denote subarrays operating at a higher and lower frequency, respectively.

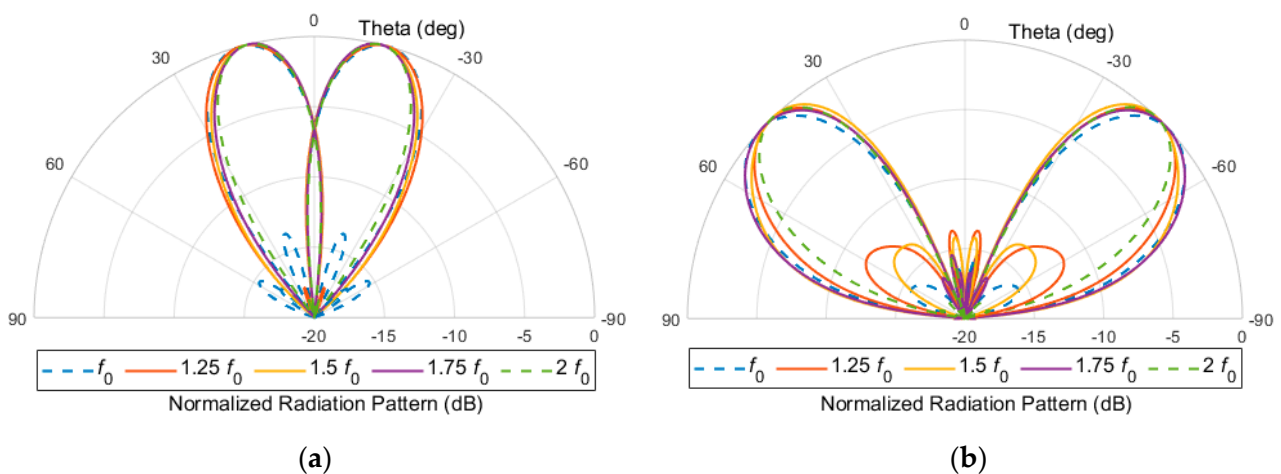


Figure 6. Calculated radiation patterns of scalable antenna array shown in Figure 5 in which a single radiating element having directive radiation pattern described by $\cos^{1.3}(\theta)$ was assumed. (a) 1L and 1R beams and (b) 2L and 2R beams.

3. Design and Realization of Octave-Band Four-Beam Antenna Arrays

Both the proposed concepts were verified by the design and realization of four-beam antenna arrays operating in a 2–4 GHz frequency range. First, a directional filter that features the desired switching function was designed, since, among different approaches to achieve the required switching functionality, such a circuit provides the simplest solution. The proposed schematic diagram and layout of the designed filter are shown in Figure 7. As can be seen, it consists of a circuit composed of two coupled-line sections with two quarter-wave transmission lines in-between. Moreover, at one of the outputs, a Schiffman C-section is added to equalize the differential phase response between the two outputs of the directional filter. The parameters of the designed directional filter are summarized in Table 1. The designed directional filter was realized in a homogeneous symmetric stripline structure shown schematically in Figure 8, in which a thin laminate layer having thickness $h_2 = 0.1$ mm was inserted between two thick laminate layers having thicknesses $h_1 = 1.52$ mm. All layers have the same dielectric constant equal to $\epsilon_r = 3.38$. The designed directional filter was manufactured and measured. The obtained results in comparison with the electromagnetically calculated ones are shown in Figure 9. As can be seen, the appropriate switching function is achieved. Moreover, the directional filter features a good impedance match and differential phase variation not higher than $\pm 10^\circ$. It is worth underlining that the larger phase imbalance is observed around the 2 GHz and 4 GHz frequencies. This has a negligible impact on the antenna array, since, in these regions, the magnitude difference for the LF and HF paths becomes large. Furthermore, the use of the filter provides almost constant gain across the one-frequency octave of the resulting antenna arrays. The performed simulation reveals that the gain change does not exceed ± 1 dB for all beams of the eight-element array and 1L and 1R beams of the twelve-element antenna array and it does not exceed ± 1.5 dB for 2L and 2R beams of the twelve-element array.

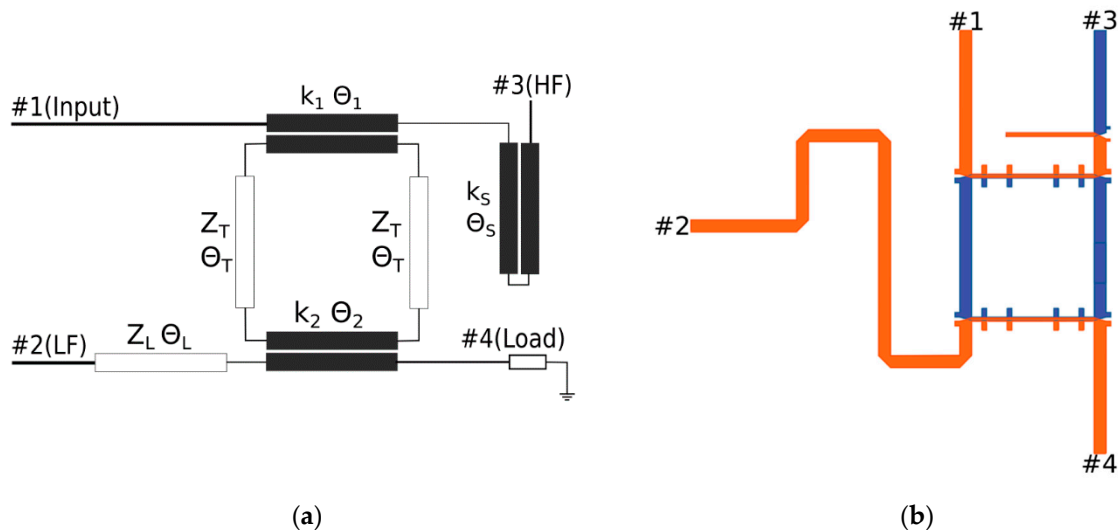


Figure 7. (a) Schematic diagram and (b) layout of the directional filter utilized in the design of a four-beam antenna array operating in an octave frequency range.

It has to be underlined that both proposed feeding networks allow good radiation properties of the resulting scalable antenna arrays to be achieved. Moreover, they are much simpler and easier to design than the solution described in [23], where the concept of a four-beam antenna array operating in an octave frequency range is shown. This is due to the fact that broadband Butler matrices, power dividers and directional filters are well known, whereas the feeding network proposed in [23] requires a very complicated modified Butler matrix, which consists of different types of directional couplers that change their properties over the bandwidth.

Table 1. Electrical parameters of the developed directional filter utilized in the design of a broadband four-beam antenna array.

| Parameter | Value |
|-------------------------|-------|
| k_1 | 0.818 |
| k_2 | 0.793 |
| k_5 | 0.784 |
| Z_T [Ω] | 50 |
| Z_L [Ω] | 50 |
| Θ_1 [$^\circ$] | 90.0 |
| Θ_2 [$^\circ$] | 90.0 |
| Θ_5 [$^\circ$] | 59.8 |
| Θ_T [$^\circ$] | 90.0 |
| Θ_L [$^\circ$] | 298.0 |

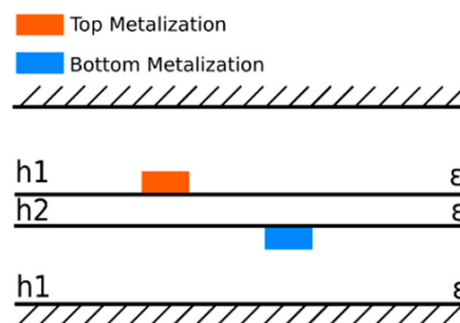


Figure 8. Cross-sectional view of the dielectric structure used for the developed directional filter.

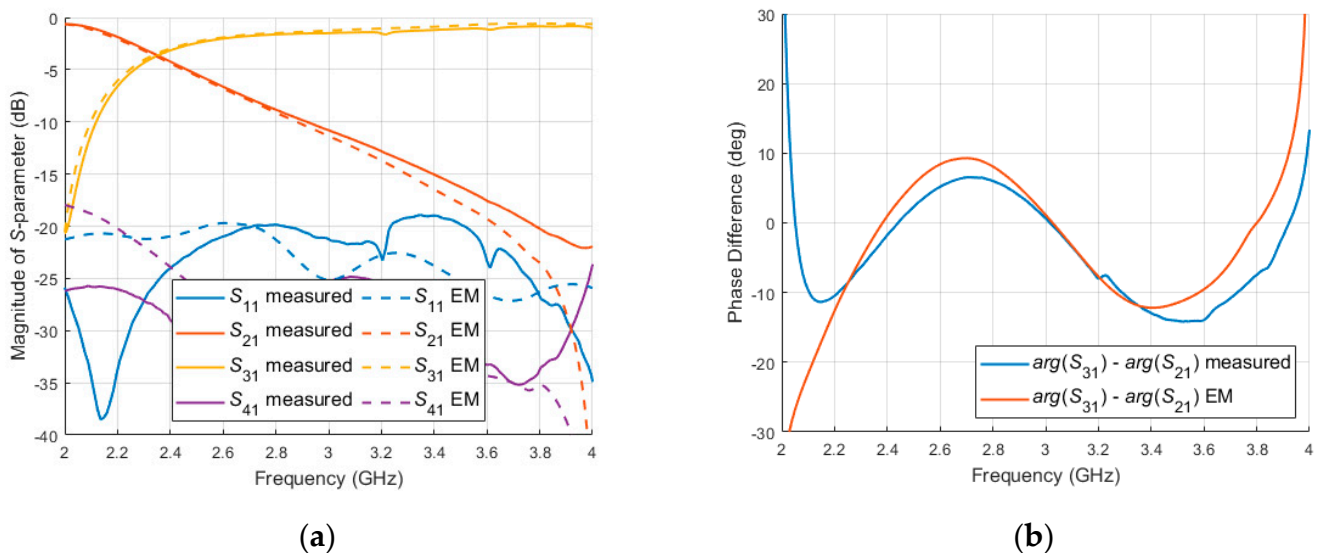


Figure 9. (a) Amplitude and (b) differential phase characteristics of the developed directional filter.

As a single radiation element, a linearly tapered slot antenna, shown in Figure 10, was selected. Such a radiating element ensures very broad bandwidth, sufficient to cover one frequency octave on one hand and a stable radiation pattern over the bandwidth on the other hand [26–28]. The linearly tapered slot antenna was optimized for operation in the 2–4 GHz frequency range. The obtained layout showing all the dimensions is presented in Figure 10 and in Table 2. The calculated reflection coefficient in comparison to the measured one is shown in Figure 11 and is better than -10 dB within the required bandwidth. Although some discrepancies between the simulated and measured reflection

coefficients are seen, most likely caused by the inaccuracy of the FR4 dielectric permittivity determination, the designed radiating element features good impedance match in the required bandwidth.

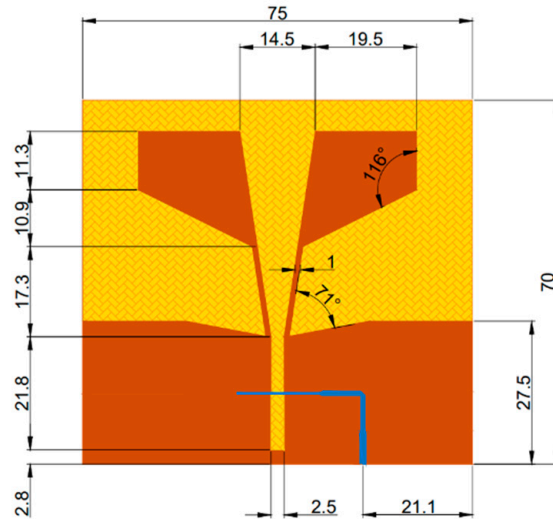


Figure 10. Layout of the single radiating element utilized in a broadband four-beam antenna array. The dimensions are given in mm.

Table 2. Physical dimensions of the feeding line in the developed radiating element, where L is length and W is width of the line.

| Dimension | Value (mm) |
|-----------|------------|
| L_1 | 5.8 |
| W_1 | 1.195 |
| L_2 | 15.6 |
| W_2 | 0.8 |
| L_3 | 16 |
| W_3 | 0.3 |

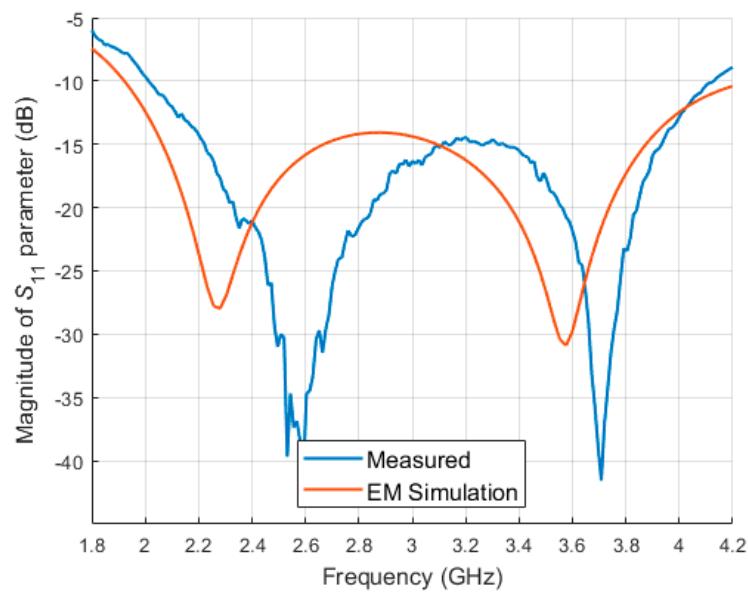


Figure 11. Calculated and measured reflection coefficients of the developed single radiating element utilized in a broadband four-beam antenna array.

The radiating element was measured in an anechoic chamber. It was placed on the 3D-printed rail using plastic screws to avoid a negative impact on the radiation pattern. A reference horn antenna was placed on the other side of the anechoic chamber at a distance of 4 m. Both the reference antenna and the manufactured element were connected to the two-port vector network analyzer. Figure 12 presents the calculated and measured radiation patterns of the developed linearly tapered slot antenna element and it is seen that the designed radiating element exhibits a wide beamwidth over the entire bandwidth, which is significant for applications in multi-beam antenna arrays.

The developed radiating element was used in both concepts of scalable four-beam antenna arrays. The feeding network and the rail containing radiating elements were mounted on the back and front of the robotic arm, respectively. The feeding network was connected to the antenna array using SMA cables. Both reference antenna and antenna array were connected to the two-port vector network analyzer. As it is seen in Figures 1 and 5, the feeding networks for both eight-element and twelve-element scalable antenna arrays have four ports so, for each of the ports, a separate measurement was conducted. During the measurements, one of the feeding network's ports was connected to the network analyzer, whereas the other ports were terminated with 50 Ohm impedance. Figure 13 presents the radiation pattern of the eight-element antenna array in which additional attenuators and the radiation pattern of a single radiating element were taken into account. As can be seen, the application of such a radiating element slightly deteriorated the sidelobe level of the antenna array, but they were at an acceptable level since they did not exceed -8 dB. The developed radiating element and directional filter together with the previously developed broadband Butler matrix described in detail in [19] were utilized to realize the broadband four-beam antenna array. The used Butler matrix exhibits both return loss and isolation not worse than 20 dB and its transmission imbalance does not exceed ± 1 dB/ 8° over the frequency of interest. Additionally, two 3 dB attenuators were added at the appropriate outputs of the Butler matrix. The assembled model of the four-beam antenna array was measured in an anechoic chamber. The obtained results are shown in Figure 14. It can be seen that good radiation properties were achieved, i.e., the antenna array features constant beam directions and beamwidths. The achieved beamwidths' variation does not exceed $\pm 4^\circ$ for 1L and 1R beams and $\pm 6^\circ$ for 2L and 2R beams, whereas the direction change does not exceed $\pm 4^\circ$ for 1L and 1R beams and $\pm 2.5^\circ$ for 2L and 2R beams, respectively.

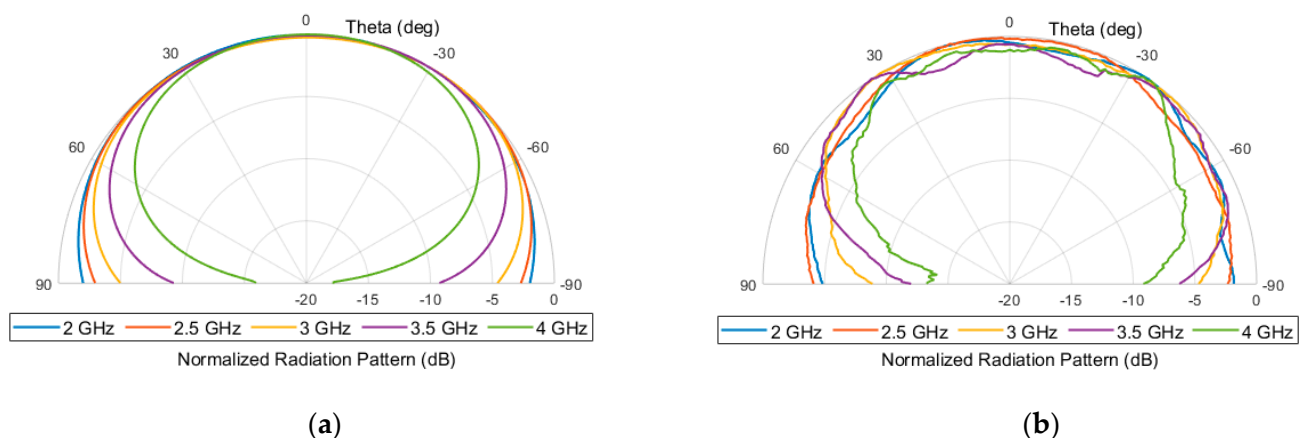


Figure 12. (a) Calculated and (b) measured radiation patterns of the single radiation element utilized in a broadband four-beam antenna array.

Similarly, the concept of a scalable antenna array composed of twelve radiating elements was verified experimentally. The calculated radiation pattern in which the radiation pattern of the developed radiating element is taken into account is shown in Figure 15. In addition, in this case, a good sidelobe level was achieved; however, a larger difference of the beamwidths caused by the directivity of the entire array is noticeable. The designed antenna array was developed based on the same components as in the case of

eight-element antenna array. Additionally, in this case, two simple power dividers were developed to assemble the entire scalable antenna array. The obtained radiation pattern of the manufactured four-beam scalable antenna array is shown in Figure 16. As can be seen, the achieved beamwidths' variation does not exceed $\pm 4^\circ$ for 1L and 1R beams and $\pm 18^\circ$ for 2L and 2R beams, whereas the direction change does not exceed $\pm 2.5^\circ$ for 1L and 1R beams and $\pm 7^\circ$ for 2L and 2R beams, respectively.

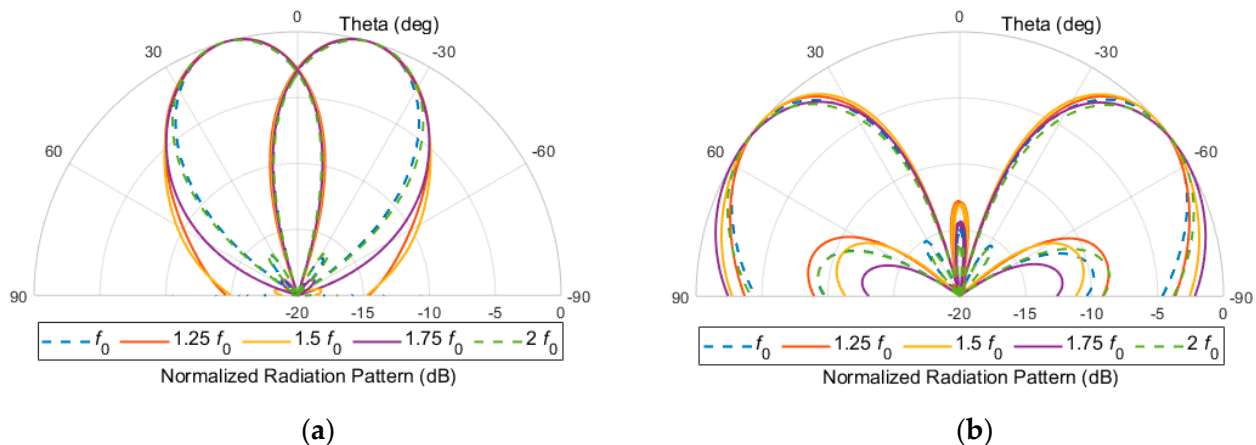


Figure 13. Calculated radiation pattern of the scalable antenna array shown in Figure 1 in which additional 3 dB attenuators were applied in outer channels. (a) 1L and 1R beams and (b) 2L and 2R beams. For the purpose of calculations, a single radiating element having the radiation pattern shown in Figure 12a was assumed.

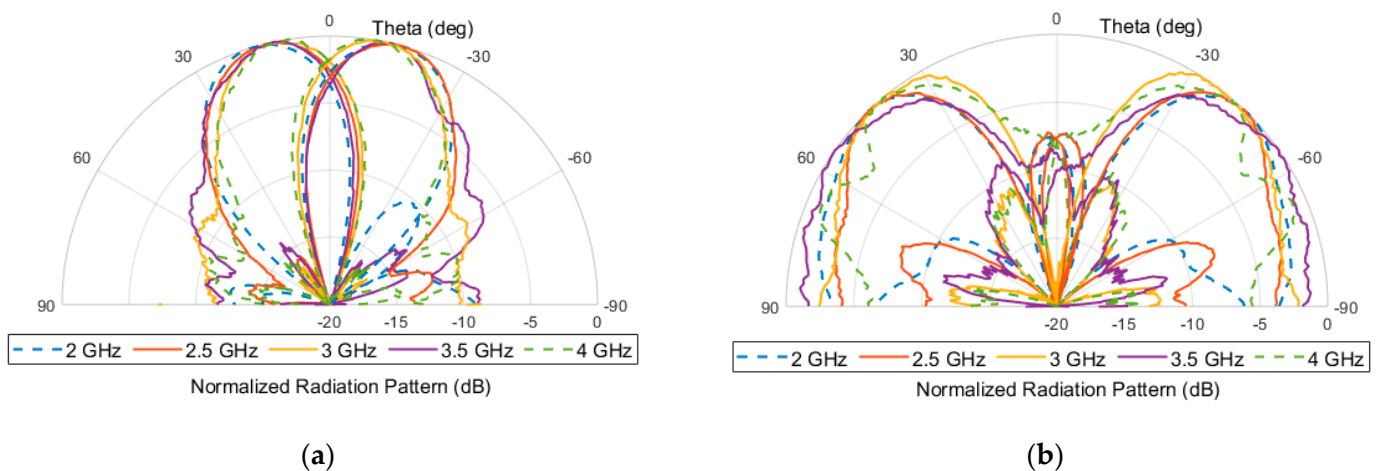


Figure 14. Measured radiation pattern of the scalable antenna array shown in Figure 1 composed of eight radiating elements and fed by a broadband 4×4 Butler matrix, directional filters and 3 dB attenuators in outer channels. (a) 1L and 1R beams and (b) 2L and 2R beams.

To complete the description of the presented design, the radiation efficiency was calculated with the use of EM simulations. For the eight-element scalable antenna array, the radiation efficiency in the frequency range of interest varies from 81.3% to 76.4%. Similarly, for the twelve-element scalable antenna array, the radiation efficiency varies between 77.9% and 71.3%. Moreover, the measured radiation efficiencies for both antenna arrays possess similar behavior to the calculated ones. The measured radiation efficiency varies from 63.2% to 55.2% and from 54.6% to 47.4% for the eight-element array and the twelve-element array, respectively. The main cause for the disproportion between EM simulations and measurements is the EM simulation setup. During simulations, an ideal and lossless, apart from the 3 dB attenuators, feeding network was assumed. Such a condition cannot be met

during measurements because it is well known that, theoretically, lossless circuits provide some attenuation in the signal path.

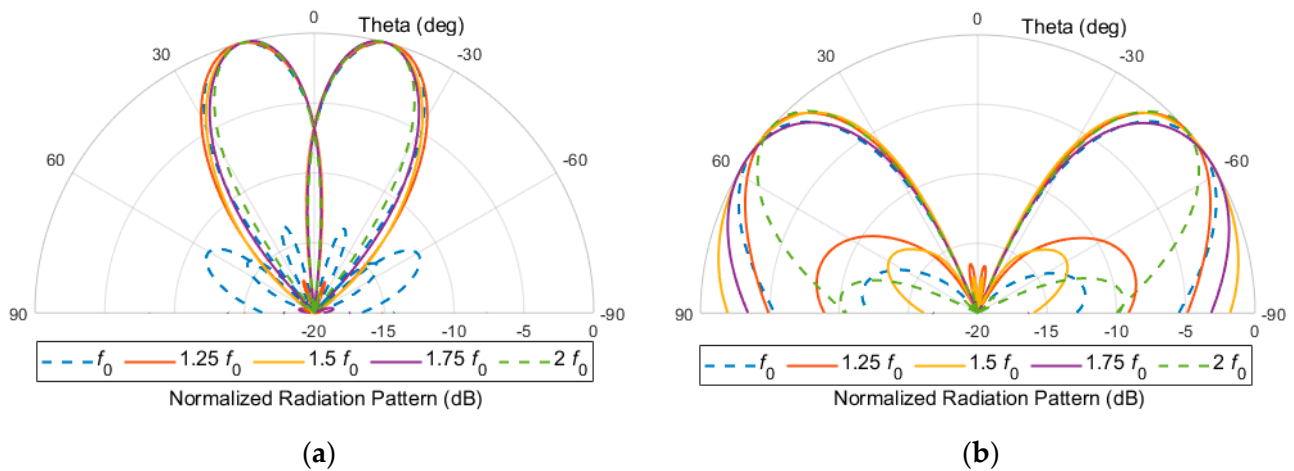


Figure 15. Calculated radiation pattern of the scalable antenna array shown in Figure 5. (a) 1L and 1R beams and (b) 2L and 2R beams. For the purpose of calculations, a single radiating element having the radiation pattern shown in Figure 12a was assumed.

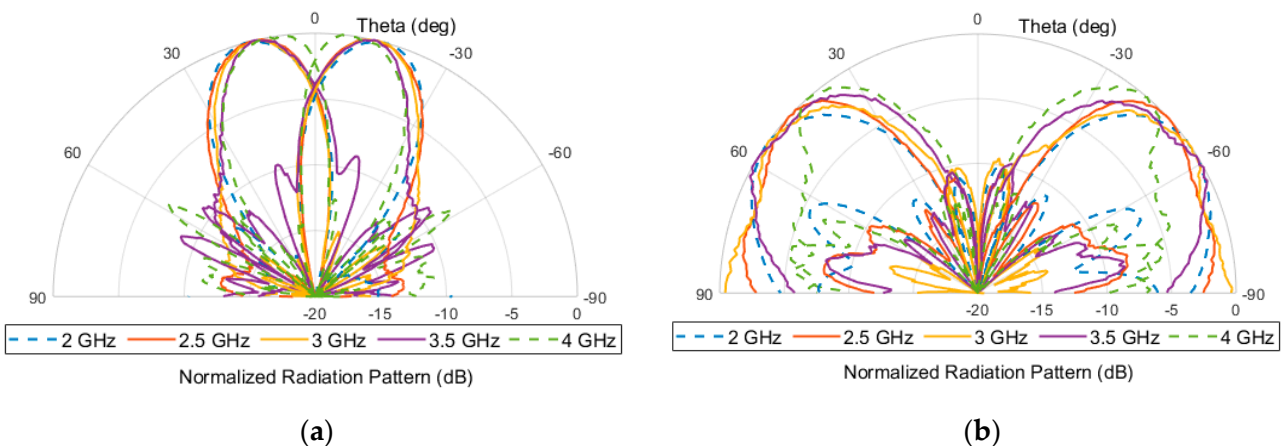


Figure 16. Measured radiation pattern of the scalable antenna array shown in Figure 5 composed of twelve radiating elements and fed by a broadband 4×4 Butler matrix, directional filters and additional power dividers. (a) 1L and 1R beams and (b) 2L and 2R beams.

The obtained measurement results reveal some discrepancies between the calculated and measured radiation patterns of both the developed antenna arrays, caused by the couplings between radiating elements, which were not taken into account during the calculations, even though both the developed scalable multi-beam antenna arrays confirm the correctness of the proposed approach and prove the possibility of the realization of four-beam antenna arrays operating in an octave frequency range with the use of the proposed approach. Figure 17 presents both the assembled models of the developed antenna arrays during measurements.

To illustrate the advantages of the presented solution against other recently reported multibeam antennas, Table 3 is presented below. As can be seen, the considered designs offer a large variety in terms of number of beams and the frequency range of operation at the expense of the overall design complexity. It can be observed that the proposed design allows four beams with the lowest variation in terms of both direction and width to be obtained and, simultaneously, it features low complexity.

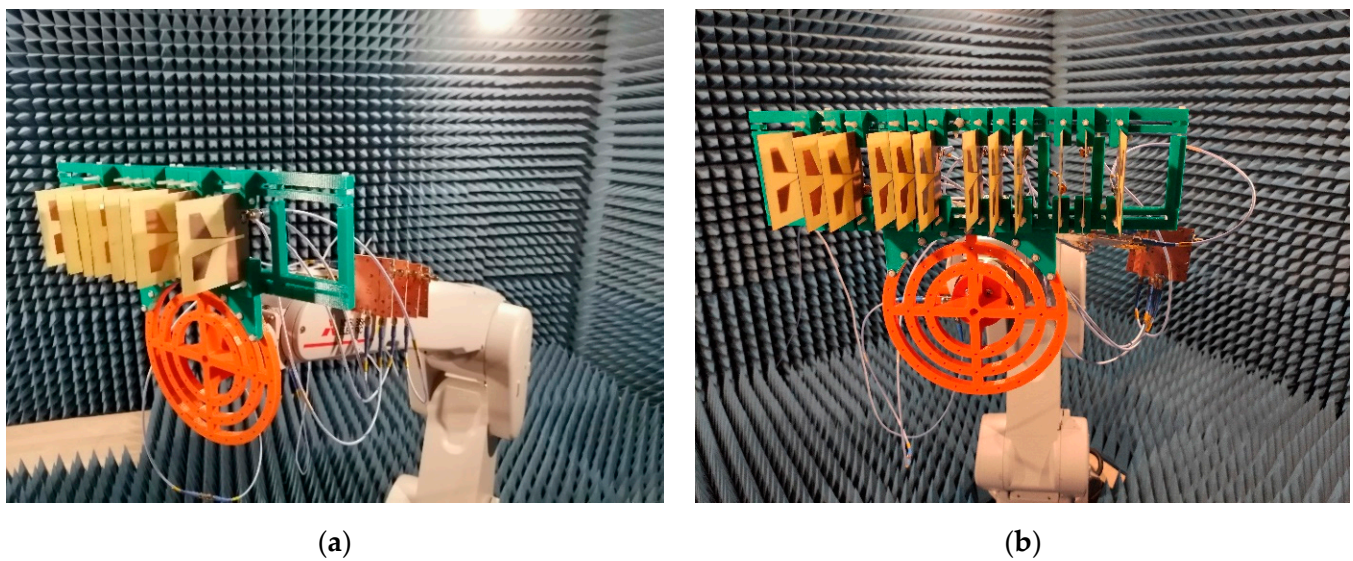


Figure 17. Pictures of the assembled models of the broadband four-beam antenna arrays during measurements. (a) The antenna arrays composed of eight radiating elements and (b) the antenna array composed of twelve radiating elements.

Table 3. Major parameters of recent multibeam antenna solutions.

| Feature | [23] | [25] | [29] | [30] | [31] | [32] | [33] | [34] | [35] | This Work |
|---------------------------|-----------------|----------------|---------------|--------|-----------|--------|----------------|-------|----------------|---------------|
| Bandwidth (GHz) | 1.75–3.5 | 1–3 | 25–30 | 12–18 | 8–10 | 5.3–12 | 6–18 | 2.5–7 | 2–4 | 2–4 |
| Bandwidth ratio f_2/f_1 | 2 | 3 | 1.2 | 1.5 | 1.25 | 2.26 | 3 | 2.8 | 2 | 2 |
| No. of beams | 4 | 2 | 16 | 7 | 4 | 5 | 8 | 9 | 3 | 4 |
| Beamwidth variation | $\pm 4.5^\circ$ | $\pm 10^\circ$ | $\pm 3^\circ$ | N/A | N/A | N/A | $\pm 20^\circ$ | N/A | $\pm 8^\circ$ | $\pm 6^\circ$ |
| Direction variation | $\pm 6.5^\circ$ | $\pm 6^\circ$ | $\pm 7^\circ$ | N/A | N/A | N/A | N/A | N/A | $\pm 10^\circ$ | $\pm 4^\circ$ |
| No. of antennas | 8 | 4 | 16 | 8 | 4 | 8 | 8 | 16 | 4 | 8 |
| Complexity | very high | low | very high | medium | very high | high | very high | high | low | low |

4. Conclusions

In this paper, a novel concept of multi-beam antenna arrays that operate over one-octave frequency range is proposed. The developed antenna arrays consist of appropriately distributed radiating elements, which are fed with the use of a classic broadband Butler matrix in conjunction with directional filters. Moreover, it is shown that, in such antenna arrays, a tapered excitation is required to improve the resulting radiation patterns. As shown, this can be achieved with either lossy or theoretically lossless feeding networks. The proposed feeding networks allow multi-beam antenna arrays that cover a broad frequency range with a relatively simple design to be realized. They also allow a stable four-beam radiation pattern to be achieved, one that is opposite to the concept presented in [25], where only a two-beam radiation pattern can be achieved. Furthermore, the proposed feeding network is much easier to design than the one presented recently in [23]. It utilizes classic well-developed components in contrast to the previously described solution, where a sophisticated Butler matrix needs to be designed to achieve appropriate amplitude and differential phase characteristics. Moreover, it has to be underlined that the concept presented in this paper can be extended to antenna arrays having more beams, e.g., eight beams, whereas frequency-dependent Butler matrices based on the concept from [23] become highly complicated and are not feasible. The proposed concept was successfully verified by the design and measurements of four-beam antenna arrays operating in the 2–4 GHz frequency range and consisting of eight and twelve radiating elements, respectively. The obtained measurement results confirm the correctness and applicability of the presented design methodology. Simultaneously, as shown in the comparison table, the presented design is of low complexity and provides stable beams over one-octave bandwidth.

Author Contributions: Investigation, A.D. and P.K.; conceptualization and supervision, K.W.; methodology, K.S. and S.G.; writing—original draft, A.D., P.K., K.S., K.W. and S.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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