Analysis of Feeding Methods for High-Gain Crossed Slot Antenna Arrays

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Abstract— **In this paper we present the influence of different feeding methods on performances of the dual polarized antenna array. Antenna array consists of 14 identical crossed slots serially fed by coplanar waveguide (CPW) and positioned at equal distances forming a linear array. Three proposed feeding methods are compared with the ideal case when two antenna sub – arrays are fed by two generators to achieve the highest possible gain. The CPW-T junction, CPW rat-race coupler and modified CPW rat-race coupler are engaged for feeding 2D crossed slots array to analyze its performances for use in 5G and radar applications.**

Index Terms—**Antenna array; CPW-fed antenna; CPW T-junction; CPW rat-race coupler; crossed slot antenna.**

I. INTRODUCTION

FOR operation at millimeter waves, antenna arrays are very attractive candidates considering high-gain and beamforming characteristic. However, the feed network, its necessary part that enables suitable amplitude and phase distributions for a large number of radiating elements in array, increases both design complexity and size of antenna. Otherwise, antennas in printed circuit technology have aroused more and more attention as one of vital components in modern 5G wireless communication system thanks to their planar structure, compact design, inexpensive and uncomplicated manufacture [1]. The printed antennas as elements in an array are usually fed by corporate-feed network, when there are a multiple lines for feeding array elements, or by series-feed network, when elements are fed by a single line. A series-feed network can be easily modeled and cheaply fabricated using simultaneous photolithography for both the radiating elements and the feed network [2,3]. However, a corporate-feed network is widely used to provide desired power splits necessary to synthesize a required radiation pattern or to achieve high side lobe suppression [4,5]. Some research has employed the combination of series and corporate feed methods to obtain the desired antenna characteristics.

There are some considerable losses typical for high operating frequency of mm-waves antennas as free-space path loss and propagation loss due to atmospheric absorption. They are both lower at the frequencies below 28 GHz wherefore the frequencies between 24.25 ï 27.5 GHz are tag as a promising operation bandwidth for the next-generation 5G networks and technologies [6]. Therefore, the antennas proposed in this paper are model and simulated for the center frequency f_c=25.875 GHz calculated as the central value of that band. This is an extension of the research presented in [7,8] that modeled the advanced high-gain rectangular slot antenna arrays fed by CPW feeding line.

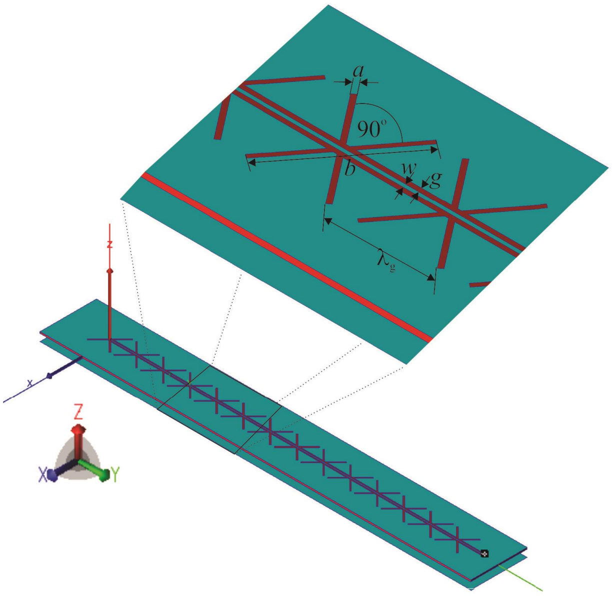

Fig. 1. Linear CPW-fed crossed slot array.

This paper analyzes firstly a linear array of identical 14 crossed slots, positioned symmetrically relative to the CPW feeding line. The crossed slot antennas, whose two rectangular parts are positioned at right angle, are dual polarized antenna with identical radiation patterns for both vertical and horizontal polarization [9]. Further, the linear crossed slot array has replicated forming CPW-fed 2D array. The following types of feeding methods are investigated: feeding by two generators for every sub ï array, CPW ïT junction, CPW rat-race coupler and modified CPW rat-race coupler. The simulated results, especially gain and bandwidth, obtained by WIPL-D Pro CAD [10] software are discussed and compared.

II. LINEAR CPW-FED CROSSED SLOT ARRAY

The radiating element in proposed antennas is a crossed slot that consists of two rectangular parts with dimensions a x b - slot width x slot length, positioned at right angle to each other [9]. The identical fourteen crossed slots are combined to form an array (Fig 1). A series feed is in a form of coplanar

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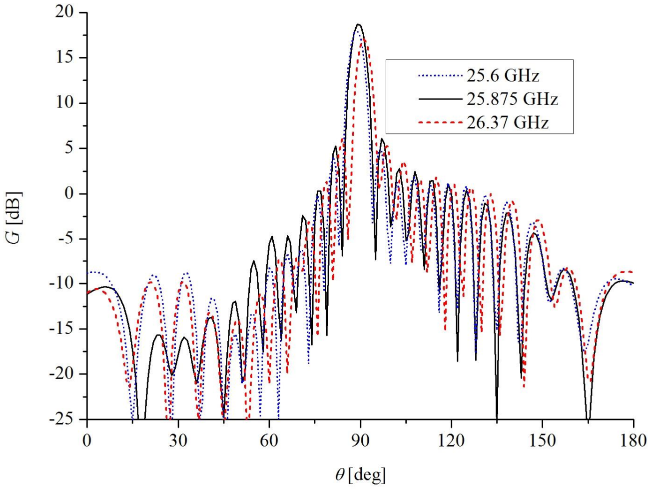

Fig. 2. Radiation patterns in the yOz plane (φ=90°) of the proposed 14 crossed slots antenna array.

waveguide (CPW) transmission line with strip and gap (w and g) of 0.3 mm and 0.375 mm, respectively resulting in characteristic impedance around 120 q. The slots are positioned symmetrically along to the CPW feeding line at the mutual distance λ_g=9 mm where λ_g is CPW line wavelength at the center frequency f_c. Their dimension a=0.44 mm and b=10.84 mm are optimized at an operating frequency f_c [9]. The proposed antenna design is built on a substrate that has a dielectric constant (e_r) of 2.54 and the dimensions 145 mm x 19 mm x 0.508mm. At the distance $\lambda_0/4$ =2.89 mm from the array there is a reflector plate whose dimension are the same as the substrateôs dimensions (λ_0 is the wavelength in vacuum at the center frequency f_c=25.875 GHz). Unlike the microstrip antennas with a backside ground plane, slot antennas require the reflector plane to be at a distance equal to the quarter of the free space wave-length. It should ensure that the antenna radiates only in half the space.

Fig. 2 shows the radiation patterns of the proposed 14 crossed slot antenna array at three frequencies: center f_c, lower (25.6 GHz) and higher (26.37 GHz) edge frequencies. The edge frequencies are determined by the criteria that the maximum gain at an edge frequency does not vary more than 10% of the maximum gain at the center frequency and that its side lobe suppression (SLS) is bigger than 10 dB. The maximum gain of the proposed 14 crossed slots antenna array at the center frequency f_c is 18.7 dBi while it is 18 dBi at the lower and 17 dBi at the higher edge frequency. The antenna has its maximum gain for θ=89° at lower edge frequency, for θ=90° at center frequency f_c and for θ=91° at higher edge frequency. Moreover, its SLS is 12.5 dB at the center frequency while it is 13 dB at the lower and 11 dB at the higher edge frequency. Its S_{11} parameter, normalized to the impedance of CPW feeding line (120 Ý), is depicted in Fig. 3. It is less than -10 dB for the frequency range between 25.6 GHz and 26.74 GHz which is more than range determined by radiation pattern.

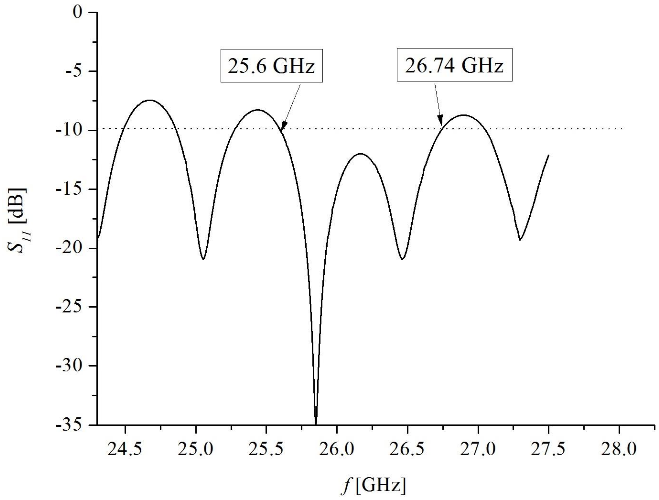

Fig. 3. S_{11} parameter versus frequency of the proposed 14 crossed slots antenna array. S-parameters are normalized to the 120 Ý -impedance of CPW feeding line.

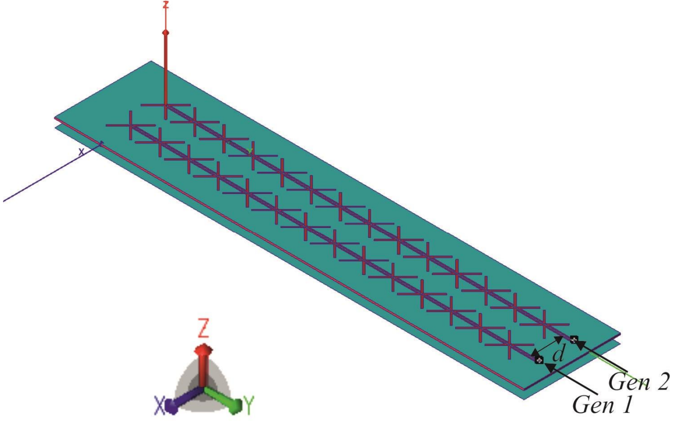

Fig. 4. 2D CPW-fed crossed slot array fed by two independent generators.

III. 2D CPW-FED CROSSED SLOT ARRAY

Two identical linear 14 crossed slot sub ï arrays, presented in previous section, are associated together at the mutual distance d=10.8 mm building a 2D array (Fig. 4). It is situated on the substrate with dimensions 145 mm x 29.8 mm x 0.508 mm while the equal reflector plate is at the distance $\lambda_0/4$.

The feed structure, required to enable equal amplitude and phase distribution for both subarrays, must be designed in order to achieve the best radiation and bandwidth properties. Therefore, different feeding techniques are modeled and studied: feeding by two generators for every sub ï array, CPW ïT junction, CPW rat-race coupler and modified CPW rat-race coupler.

A. Feeding by Two Generators

In the first study, the two sub-arrays are fed by two generators placed at the end of CPW lines (Fig. 4). Due to the influence of the mutual coupling between sub-array in x-axis direction, the dimensions of crossed slot antennas are optimized to the different values a=0.53 mm and b=10.78 mm in the respect to the linear array. The radiation patterns of 2D crossed slots antenna fed by two generators is depicted in Fig. 5.

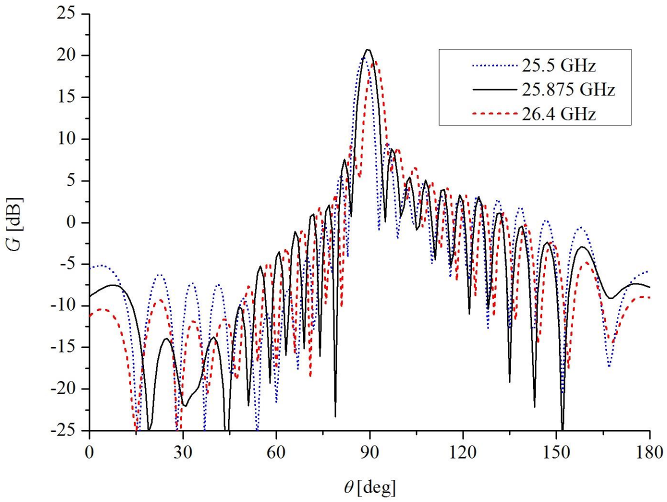

Fig. 5. Radiation patterns in the yOz plane (φ=90°) of the 2D CPW-fed crossed slots array fed by two independent generators.

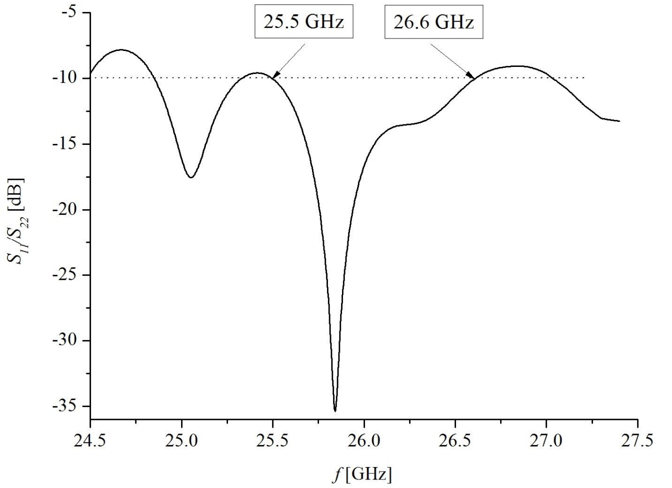

Fig. 6. S_{11} and S_{22} parameter versus frequency of the 2D CPW-fed crossed slots array fed by two generators. S-parameters are normalized to the 120 Ý - impedance of CPW feeding lines.

Because there are two sub-arrays of 14 crossed slots, the gain at the center frequency f_c is 20.7 dBi (θ=90°). At the edge frequencies the gain drops off a bit: it is 19.9 dBi (θ=88°) at lower edge frequency (25.5 GHz) and 19.3 dBi (θ=92°) at higher edge frequency (26.4 GHz). SLS is 12 dB at the center frequency f_c while it falls to 10 dB at the edge frequencies. However, as the previously discussed linear 14 crossed slots antenna, the proposed 2D CPW-fed crossed slots antenna has the bigger range where its S_{11} parameters (Fig. 6), normalized to the 120 Ý -impedance of CPW feeding line, is less than -10 dB (25.5 GHz ï 26.6 GHz) then the range of the satisfying radiation patterns (25.5 GHz ï 26.4 GHz). Besides very good radiation properties of the proposed 2D crossed slots antenna fed by two generators, it is necessary to design the unique feed to enable the uniform amplitude and phase distribution for both arrays and therefore CPW T-junction and CPW race rat couplers are introduced.

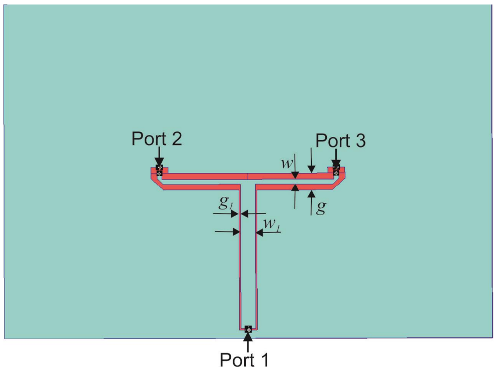

Fig. 7. CPW-T junction.

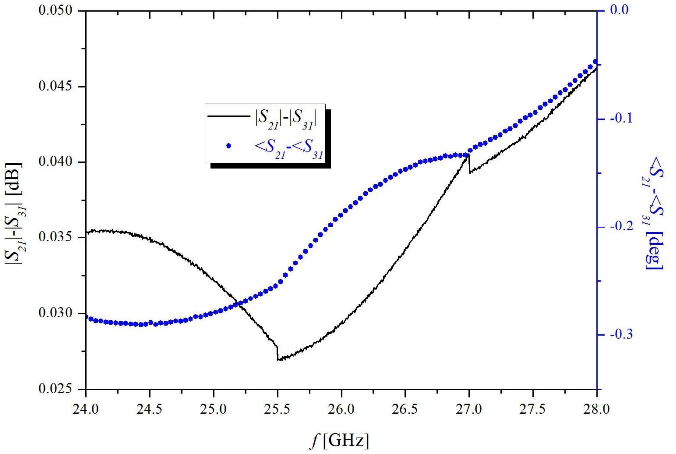

Fig. 8. The difference between insertion losses calculated at ports 2 and 3 of CPW T-junction. S-parameters are normalized to the impedance of CPW feeding line (120 Ý).

B. CPW – T junction

Further, the 2D array is fed by the T junction power divider implemented with coplanar waveguide transmission lines (CPWïT junction). Configuration of the proposed CPW power divider is shown in Fig. 7. The CPW feed line is 60 Ý-CPW line (featuring the strip w_1=0.9 mm and gap g_1=0.1 mm), that enables equal feeding for both sub - arrays dividing power into two 120 Ý CPW feed lines featuring the strip w=0.3 mm and gap g=0.375.

The difference between S-parameters (magnitudes ($|S_{ij}|$) and phases ($\angle S_{ij}$) of S_{21} and S_{31} S scattering (S-) parameters for left and right subarrays) is presented in Fig. 8. Analyzing shown results, it can conclude that proposed CPW T junction provides necessary equal feeding for both subarrays for range between 24-28 GHz. Therefore, CPW T-junction is used to feed the 2D crossed slots array. The whole structure, 2D array and CPW T-junction, is situated on the substrate with dimensions 150 mm x 29.8 mm x 0.508 mm while the equal reflector plate is at the distance $\lambda_0/4$ (Fig. 9).

The Fig. 10 presents the radiation pattern of 2D crossed slots array fed by CPW T-junction. The radiation pattern at the center frequency f_c features with gain of 18.45 dBi at θ=90° and SLS of 12 dB. At the lower edge frequency (25.49 GHz) the gain is 18.16 dBi at θ=88°. At the higher edge frequency (26.45 GHz) the gain is 17.48 dBi at θ=92°. SLS for both edge frequencies is 10 dB. S_{11} parameter is less than -10 dB for the frequency above 25.49 GHz (Fig.11).

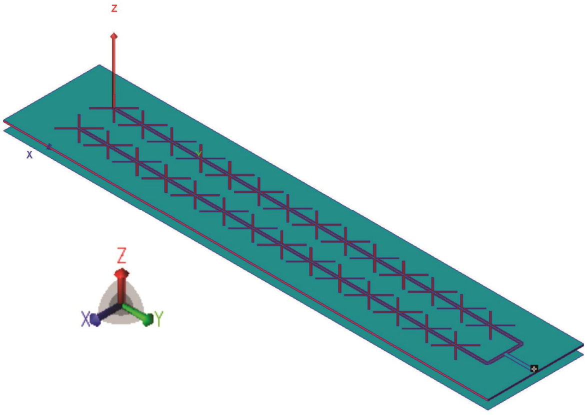

Fig. 9. 2D CPW-fed crossed slot array fed by CPW T-junction.

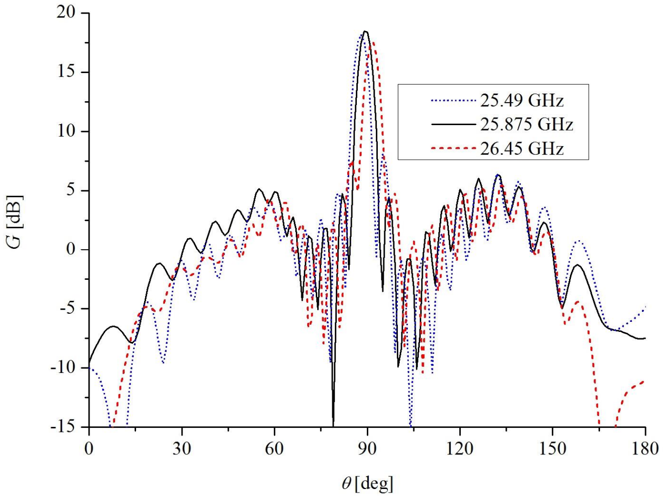

Fig. 10. Radiation patterns in the yOz plane (φ=90°) of the 2D CPW-fed crossed slots array fed by CPW T-junction.

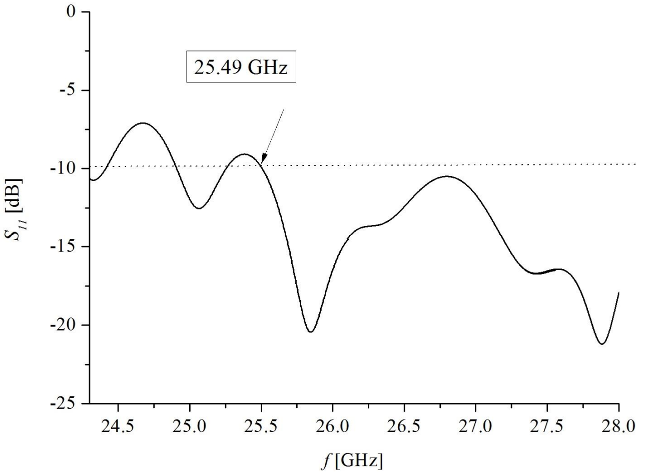

Fig. 11. S_{11} parameter versus frequency of the 2D CPW-fed crossed slots array fed by CPW T-junction. S-parameter is normalized to the impedance of CPW feed line 60 Ý.

C. *CPW rat-race coupler*

The additional research employs CPW rat-race coupler, with the shape of a ring/circle, to provide required feeding for both sub-arrays. Rat race couplers have been very attractive for use in many applications such as mixers, multipliers, amplifiers, beamformers, etc. [11]. One of its disadvantages is that its big circumference ($3\lambda_g/2$) requests too much space increasing the overall size of antennas.

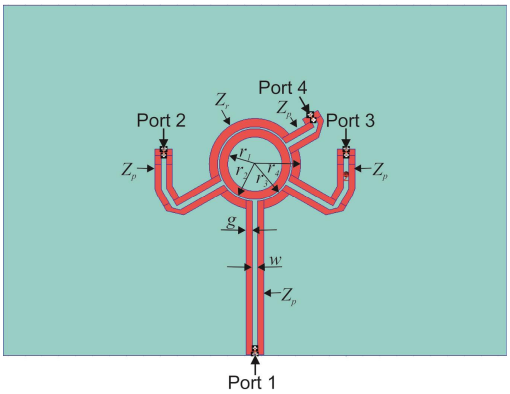

Fig. 12. CPW rat-race coupler.

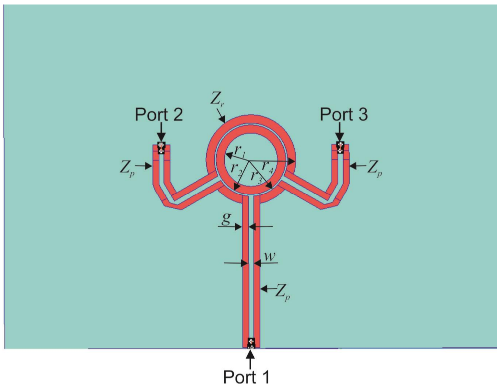

Fig. 13. Modified CPW rat-race coupler.

The proposed CPW rat-race coupler has 4 ports with Z_p=120 q impedance as numbered in Fig. 12, each of which is presented by CPW feed line featuring the strip w=0.3 mm and gap g=0.375. Each port is placed at a distance of one-quarter wavelength (λ_g) away from the other around the one half of the ring. The CPW forming the ring has a impedance Z_r=ã2*Z_p=ã2*120=169.7 q with gap g_r=0.5 mm and strip width w_r=0.105 mm. The CPW rat-race ring features the following radius: r_1=1.6 mm, r_2=2.1 mm, r_3=2.205 mm and r_4=2.705 mm.

An input signal is fed from port 1 resulting in two equal amplitude in-phase signals at ports 2 and 3. Port 4 is isolated in this case. Therefore, ports 2 and 3 are used to feed two identical linear 14 crossed slot sub ï arrays while port 4 is connected to the ground through the impedance of 120 q. Although there are two sub-arrays, we model likewise a modified CPW rat-race that does not contain port 4 (Fig. 13) in order to investigate its role and necessity in rat-race coupler.

The imbalance between S-parameters (magnitudes ($|S_{ij}|$) and phases ($\angle S_{ij}$) of S_{21} and S_{31} S scattering (S-) parameters referring Port 2 and Port 3 of both CPW rat-race coupler and modified CPW rat-race coupler for feeding left and right subarrays) for frequency range from 24 GHz to 28 GHz is presented in Fig. 14. Analyzing shown results, it can see that maximum difference between magnitudes of S_{21} and S_{31} parameters of rat-race coupler with 4 ports is less than 0.5 dB while the maximum variation between their phases is less than 2.5 degrees. Modified rat-race coupler enables equal amplitude in-phase signals at ports 2 and 3 concerning results shown in Fig. 14.

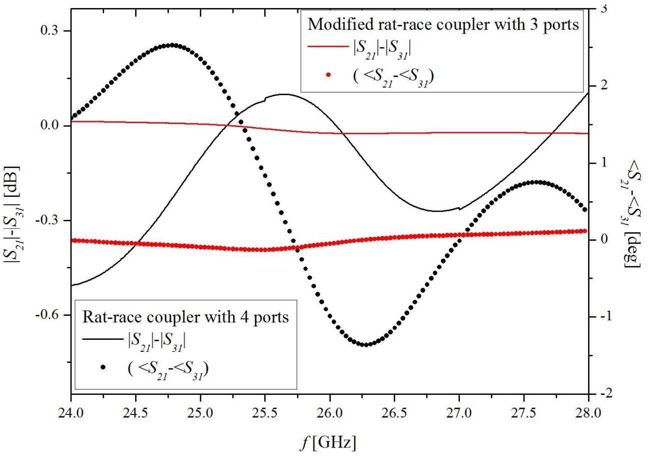

Fig. 14. The difference between insertion losses calculated at ports 2 and 3 of CPW rat-race coupler and of modified CPW rat-race coupler. S-parameters are normalized to the impedance Z_p (120 Ý).

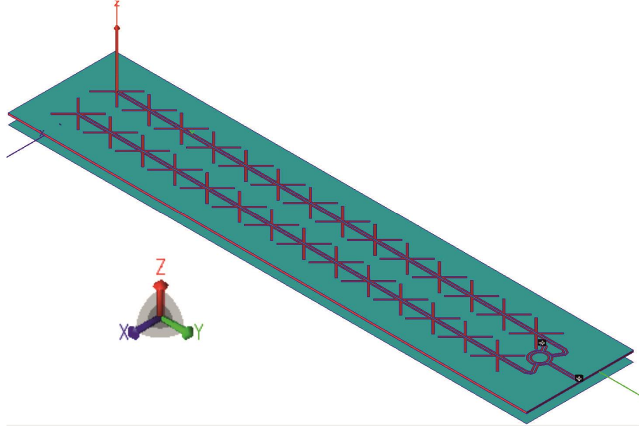

Fig. 15. 2D CPW-fed crossed slot array fed by CPW rat race coupler.

It can be concluded that proposed both CPW rat-race coupler and modified CPW rat-race coupler provide necessary feeding for both subarrays for range between 24-28 GHz. Therefore they are employed to feed 2D crossed slots array (Fig. 15). 2D crossed slots array and CPW rat-race coupler are both situated on the substrate with dimensions 145 mm x 29.8 mm x 0.508mm while the equal reflector plate is at the distance $\lambda_0/4$.

The radiation patterns of 2D CPW-fed crossed slots array fed by CPW rat-race coupler with 4 ports is presented in Fig. 16. The maximum gain at the center frequency f_c is 19.6 dBi at the position θ=90°. At the lower edge frequency 25.6 GHz, the maximum gain is 18.8 dBi at the position θ=89°. At the higher edge frequency 26.8 GHz, the maximum gain is 18.65 dBi at the position θ=93°. SLS is 12.5 dB at the center frequency f_c and 10 dB at the both edge frequencies.

However, the radiation pattern of the 2D CPW-fed crossed slots array fed by modified CPW rat-race coupler with 3 ports has less gain for all considered frequencies (Fig. 17): 18.85 dBi at the center frequency f_c, 18.4 dBi at the lower edge frequency 25.6 GHz and 18.6 dBi at the higher edge frequency 26.6 GHz. The maximum gain spreads from θ=89° for the lower edge frequency 25.6 GHz, through θ=90° for f_c to θ=93° for the higher edge frequency 26.6 GHz. SLS is 12 dB at the center frequency f_c and it drops to 10 dB at the edge frequencies.

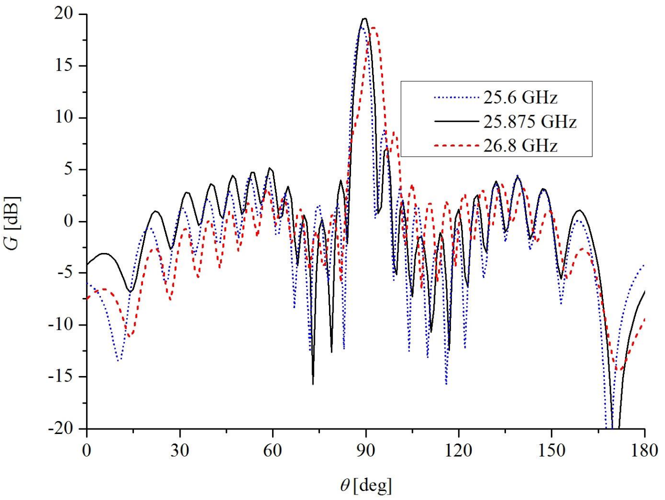

Fig. 16. Radiation patterns in the yOz plane (φ=90°) of the 2D CPW-fed crossed slots array fed by CPW rat-race coupler.

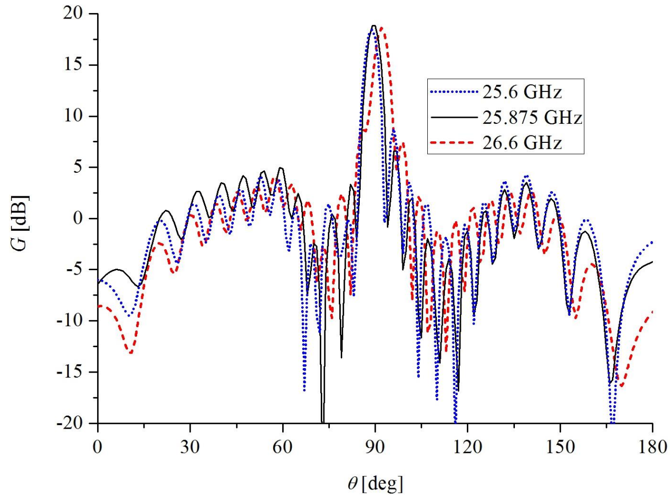

Fig. 17. Radiation patterns in the yOz plane (φ=90°) of the 2D CPW-fed crossed slots array fed by modified CPW rat-race coupler.

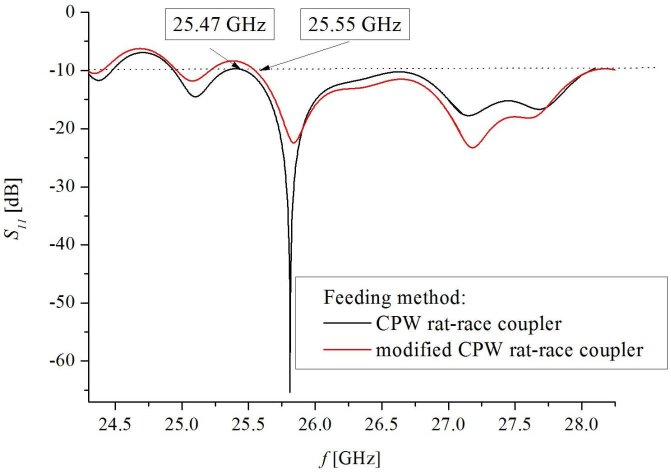

Fig. 18. S_{11} parameter versus frequency of the 2D CPW-fed crossed slots array fed by CPW rat-race coupler and by modified CPW rat-race coupler. S-parameter is normalized to the impedance Z_p=120 Ý.

The S_{11} parameter of 2D CPW-fed crossed slots array fed by CPW rat-race coupler and by modified CPW rat-race coupler is shown in Fig. 18.

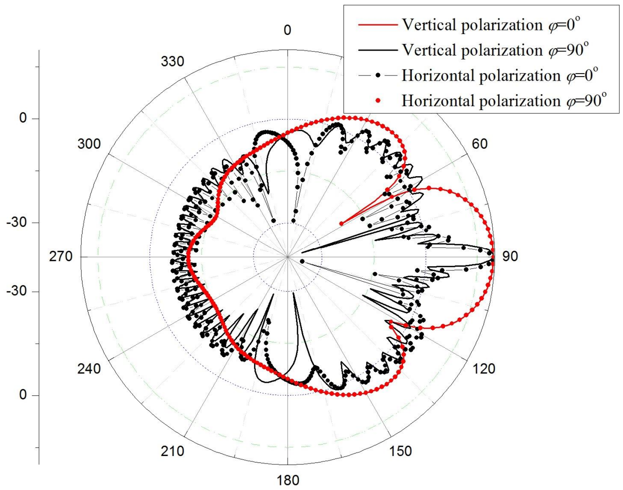

Fig. 19. Radiation pattern of the 2D CPW-fed crossed slots array fed by CPW rat-race coupler in X-Z (φ=0°) and Y-Z (φ=90°) plane at the frequency f_c.

TABLE I

THE GAIN AND BANDWIDTH DEFINED BY RADIATION CHARACTERISTICS AND BY S_{11} PARAMETERS OF THE PROPOSED LINEAR AND 2D CPW-FED CROSSED SLOT ARRAYS

Array and feed	Gain [dBi]	Bandwidth by radiation pattern/by S_{11} [GHz]
14 slots	18.7	0.77/1.14
2x14 slots by 2 generators	20.7	0.9/1.1
2x14 slots by CPW T-junction	18.45	0.96/>2.51
2x14 slots by CPW rat-race	19.6	1.2/>2.53
2x14 slots by modified CPW rat-race	18.85	1/>2.45

It is less than -10 dB for frequency above 25.47 GHz for feeding by CPW rat-race and for frequency above 25.55 GHz when the modified CPW rat-race is used. It can notice that 2D CPW-fed crossed slots array fed by CPW rat-race coupler has the biggest frequency range defined by both criteria: by satisfying radiation characteristics and by condition that S_{11}<-10 dB. Also, the latter criterion gives greater frequency range than the former.

Although the single crossed slot antenna is dual polarized [9], the simulated radiation patterns in both X-Z and Y-Z planes for two orthogonal polarizations (vertical and horizontal) of the 2D CPW-fed crossed slots array fed by CPW rat-race coupler are presented in Fig. 19. It can conclude that it is also a dual polarized antenna.

All obtained results of comparison between feeding methods and antenna arrays are shown in Table I.

IV. CONCLUSION

This paper presents the antenna arrays of crossed slot antenna fed by CPW transmission line. The first proposed antenna is a linear array of 14 crossed slots that features with gain of 18.7 dBi at the center frequency f_c. It has the satisfying radiation patterns from the frequency range from 25.6 GHz to 26.37 GHz. Also, its S_{11} parameter is less than -10 dB for the frequencies between 25.6 GHz to 26.74 GHz.

After that we investigate feeding networks for two planar arrays of 14 crossed slots and employ four feeding methods. First method is two generators that enable great gain of 20.7 dBi of the proposed 2D crossed slot array. The gain and SLS have the allowed variation for the frequency range from 25.5 GHz to 26.4 GHz. Moreover, S_{11} parameter stays below -10 dB for the frequencies between 25.5 GHz to 26.6 GHz.

CPW T-junction, CPW rat-race coupler and modified CPW rat-race coupler are proposed. The comparison among the simulated results of investigated three feeding methods gives the advantage to the CPW rat-race coupler. The gain is the greatest when CPW rat-race coupler is used (19.6 dBi). Additionally, the radiation pattern keeps the satisfying gain and SLS values in the largest frequency range when 2D array is fed by CPW rat-race coupler (25.6 GHz - 26.8 GHz). However, S_{11} parameter of 2D array fed by CPW rat-race coupler is less than -10 dB for the similar frequency range above 25.47 GHz as S_{11} parameter of 2D array fed by CPW T-junction and S_{11} parameter of 2D array fed by modified CPW rat-race coupler.

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