Microstrip antenna design for arrays generating OAM mm-wave radio signals

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Abstract. The paper is devoted to the development of the single antenna as an element of the array, intended for radiating electromagnetic fields with different orders of the orbital angular momentum (OAM) in the band 77 ÷ 78.5 GHz. Multiplexing by OAM provides more opportunities for safe data transmission and increases the quantity of the simultaneously transmitted channels. The antenna design takes into account the special requirements for its structure, imposed by its practical usage in the array. The modeling process includes calculating the dimensions, selecting the suitable materials (Rogers RO 3003) and components, simulating with the software and analyzing the following characteristics: VSWR, return loss S₁₁, input impedance, and radiation pattern. The designed antenna’s configurations correspond to a half-wave dipole, fed by coplanar waveguide port and matched to 50 Ohm impedance. The VSWR for all cases is less than 1.8, the radiation pattern is quite wide. The shape and size for the proposed antennas provide an easy combination of such elements in the array, including the issues of the feeding lines simplicity. The application areas are described.

1. Introduction

One of the main tendencies of modern wireless communication lines consists in moving to the high-frequency band, which is attractive due to the absence of severe radiation limits and a low load of its usage. Particularly W frequency band (W-band, 75-110 GHz) shows the great potential to provide 100 Gbps wireless links using existing technologies. Moreover, high frequencies lead to equipment miniaturization which is very desirable for mobile devices. In the Russian Federation, the W-subband 76-78 GHz is determined to be used for mobile applications [1].

Another promising radio technology is multiplexing the radio signals based on the orbital angular momentum (OAM) states of the electromagnetic field, which gives us a new set of basic functions to reduce the overload of frequency resources and provide high data security.

For radio beams generation with non-zero OAM state various designs for transmitting antennas are used: antenna arrays, antennas with a spiral phase plate (SPP) or metasurface plate, etc. Among them, SPP is one of the most common solutions. Based on this approach, a flat 8-element antenna array operating at 60 GHz and represented by a multilayer phase-shifting surface is proposed in [2]. To implement phase control between the incoming and outgoing vertically polarized waves the antenna array includes several conductive SPP plates separated with dielectric layers. The main disadvantage of SPP based OAM antennas is that one configuration of the SPP plate corresponds to only one OAM state of emitted radio waves.
The principle of generating OAM radio waves for metamaterial plates is similar to the SPP. The two-layer metamaterial plates are a spatial-variational lattice consisting of rectangular [3] or U-shaped [4] holes. By controlling the spatial orientation angle of the holes the required wavefront of an emitted radio signal is created.

Another common solution is the application of circular antenna arrays, elements of which are fed with the signal of uniform amplitude and different phases. The main advantage of circular antenna arrays over the approaches as mentioned above is the possibility of radio waves generation with various OAM states without changing the antenna configuration. In this way, an eight-element antenna array operating at a frequency of 2.45 GHz is presented in [5] generating radio waves of $l = \pm 1$, $l = \pm 2$, $l = \pm 3$ OAM states. The main disadvantage of this class of OAM antennas is the need to develop a complex feeding line for the array elements.

In this paper, we consider the approach based on circular antenna arrays, since it is more flexible and provides more opportunities for multiplexing channels. The prototype of such an array developed based on multipole decomposition of the electromagnetic field was presented in [6-7]. To implement it, first of all, the single antenna as an elementary radiator of the array is necessary. The main goals for its development are the ability to operate in the band of $77 \div 78.5$ GHz, compactness, simplicity, possessing the low profile and ease for combining in an array. According to the given requirements, the microstrip technology was chosen due to its application, low profile, low cost and planar configuration, apart from the ease of patch integration with the high-frequency microwave integrated circuits [8].

There are many solutions for microstrip antenna design in W-band. In [9] the rectangular microstrip antenna operating at 76 GHz is presented. The waveguide-microstrip converter is used to couple the energy into the microstrip line to feed the antenna on the substrate. The results of the simulation and experimental test showed that antenna performance is not satisfactory. The analysis of results reveals that the microstrip line affects the performance of the antenna greatly. A novel corner-fed 45-degree polarized patch array is proposed in [10]. A slot is etched on the patch to excite 45-degree polarization. Simulation results show the good performance in W-band.

Although to be applicable for circular antenna arrays designed to generate OAM signals with circular polarization, microstrip antenna must have the linear polarization. Thus, in [5] a square microstrip radiator with truncated angles is used as the element of the antenna array. The circular polarization of the antenna array is due to many factors, such as the size of the antenna, the size of truncated angles, and the position of the feeding port.

The circular patches are also commonly applied for OAM radio waves generation, both as an individual transmitting antenna and as the element of an antenna array. For example, four circular patches are used to build the OAM-generating array in [11]. To obtain a wideband operation each circular patch is composed of three substrate layers and an air-gap. A combination of a circular patch and 3 dB quadrature hybrid circuit is proposed in [12] to generate OAM radio beams with two opposite OAM states. Consequently, the circular patch is believed to be significant to the wireless applications due to its simple geometry.

Based on the state-of-the-art review we can conclude that the application of circular antenna arrays for OAM radio signals generation seems to be more promising and convenient in practice, comparing to the other solutions. So in this paper, we propose to develop and analyze different configurations of the microstrip circular patch antenna, operating in W-band and suitable for the generation of OAM signals as a part of the array.

The paper is organized as follows: In Section 2 the design aspects and parameters of the prototype for the microstrip antenna are described. Three different configurations of the proposed antenna developed based on the prototype are presented and discussed in Section 3. Section 4 describes the circular antenna array aimed at OAM radio waves generation and consisting of eight microstrip antennas with selected configuration. The conclusions and future work goals are summarized in Section 5.
2. Design of the microstrip antenna’s prototype

The review on microstrip antennas design revealed that they are aimed at radiating in higher frequency bands (80 GHz and 90 GHz), so they have an extremely small size around 1.0 mm × 1.5 mm. This fact along with their complicated structure could be a serious challenge in the manufacturing process. Another important issue consists in the fact that the presented prototypes were simulated without any connector, but it will be shown later that its choice has a serious influence on antenna’s characteristics, particularly on radiation pattern and matching.

So there are few requirements for the antenna that can be applied as an element of the array. First of all, it should operate in the desired frequency band (77÷ 78.5 GHz in our case). Its radiation pattern should be wide with the maximum oriented normal to the antenna plane. The shape for the radiating part should be chosen to provide the maximum possible gain, not less than the gain of the dipole antenna. It should be characterized by linear polarization. And finally, the construction of the antenna should provide miniaturization and simplicity of its application in the array.

In this paper, we considered the circular patch antenna as a basis for designing the other configurations, since it has a simple structure that provides wide operation frequency band and radiation pattern. The proposed prototype of the microstrip circular patch is presented in figure 1 (a).

The antenna represents a microstrip half-wave radiator, which characteristic impedance is matched to 50 Ohm. Respectively to the desired frequency band 77÷ 78.5 GHz, the Rogers RO 3003 laminate was applied for the antenna design. Its characteristics: substrate thickness – 0.5 mm; foil thickness – 35 μm; dielectric constant – 3.00±0.04; the dielectric loss tangent – 0.0010. The antenna is fed by coplanar waveguide port and the KMCO KPC100 connector, operating till 110 GHz. The main part of the radiating element has a shape of a circle with a radius of 2.2 mm. The total size of the antenna is 9.6 mm × 4.8 mm.

The return loss $S_{11}$ is shown in figure 1 (b). It is obvious, that its values are less than -10 dB in the band 76.5 ÷ 79 with the resonance at 78.395 GHz. That fact indicates that the prototype is well matched in the whole desired operating frequency band.

![Figure 1. The microstrip antenna’s prototype: (a) antenna’s view; (b) the return loss.](image)

The radiation pattern (RP) of the prototype is shown in figure 2. The main lobe has a width of more than 80°, and the realized gain is 6.27 dB. The gain can be increased by a combination of small antennas with the corresponding array factor and application of matching devices.

The other prototype’s characteristics such as real and imaginary parts of the input impedance and VSWR were calculated and demonstrated their good performance. The currents distribution was also constructed and analyzed. Summarizing, we can say that the antenna is operating in the required frequency band, has a wide radiation pattern and can be further considered in the array for generating OAM signals. However, its dimensions and operation band could be further improved by the modification of the radiator’s shape and feeding line, which will be investigated in the next Section.
3. Design of the microstrip antenna’s configurations

3.1 Configuration #1
The first configuration of the developed prototype is shown in figure 3. Firstly the circle shape was substituted by the square, and then four triangular slots were cut out from the corners of the radiating patch to enlarge the bandwidth. The length of the triangle’s sides is equal to \( \lambda / 2 \). Also, the adjustment of the feeding line provided the resonance shift to the desired operation band. The final size of the antenna is 5.14 mm \( \times \) 2.50 mm, which is almost twice smaller than the prototype. The ground plane is placed on the backside of the substrate and occupies the whole space.

![Figure 3. The view of the configuration #1: a) perspective, b) front, c) back.](image)

The return loss \( S_{11} \) in figure 4 shows that the modified resonant frequency is now 77.68 GHz, and the operating band has been increased to 76.11 ÷ 79.63 GHz (\( \Delta f = 3.52 \) GHz), which also covers the defined W-subband 77÷78.5 GHz.

![Figure 4. The return loss of the configuration #1.](image)
According to the radiation pattern in figure 5 the antenna has the realized gain 6.36 dB, which is almost the same as the prototype has. Its maximum radiation is directed perpendicularly to the antenna’s plane, which is very desirable for the array construction. The width of the main lobe at 3 dB level is 119.4°, and the side lobes level is -1.5 dB. Also, the input impedance and the currents distribution were calculated (both not presented here), which revealed that the intensity of the currents is decreasing, starting from the maximum at the feeding point and directly to the top of the antenna. The currents are distributed symmetrically regarding the vertical axes, mostly in the feeder and at the edges of the radiating element. The antenna is matched to 50 Ohm impedance with the imaginary part fluctuating around 0 Ohm level, which specifies this antenna as resonant. Thus, the first configuration provides operating in the required band and the same gain as a prototype while being twice smaller.

![Figure 5. The radiation pattern of the configuration #1 in horizontal (a) and vertical (b) planes.](image)

### 3.2 Configuration #2

The second modification was obtained by cutting four squares from the corners of the initial big square with the side equal to $\lambda/2$ (figure 6 (a)). So the shape of the radiating element became similar to the cross. Moreover, another smaller cross was cut out from the center of the radiating element: the dimensions of horizontal and vertical slots are equal to $\lambda/8 \times \lambda/2$. The total size of the antenna is the same as for the first configuration. These modifications allowed us to move the resonance lower (to 77.24 GHz) and make it deeper (almost -30 dB), and therefore to enlarge the bandwidth to 74.78 ÷ 80.23 GHz ($\Delta f = 5.45$ GHz), which is confirmed by the return loss $S_{11}$, presented in figure 6 (b).

![Figure 6. The front view of the configuration #2 (a) and its return loss (b).](image)

The price of wide bandwidth is the realized gain of the second configuration equal to 3.84 dB, which is almost twice less than in the previous case. The RP is shown in figure 7. The impedance and currents distribution are similar to the configuration #1 with the only difference, consisting in quite significant currents intensity around the cross slot, which defines this antenna as a slot antenna. Summarizing configuration #2 provides wider bandwidth but less gain.

### 3.3 Configuration #3

The last configuration represents the combination of two previous modifications, i.e. it has cross slot inside and four triangular cuts outside. The total dimensions remain the same (figure 8 (a)). For that
case, we obtained the bandwidth 76 ÷ 80.0 GHz ($\Delta f = 4$ GHz), as shown in figure 8 (b), and the gain 6.25 dB (figure 9).

![Figure 7](image1.png)  
**Figure 7.** The radiation pattern of the configuration #2 in horizontal (a) and vertical (b) planes.

![Figure 8](image2.png)  
**Figure 8.** The front view of the configuration #3 (a) and its return loss (b).

![Figure 9](image3.png)  
**Figure 9.** The radiation pattern of the configuration #3 in horizontal (a) and vertical (b) planes.

### 3.4 Analysis of the proposed antenna’s configurations

According to the calculated characteristics of the proposed microstrip antenna configurations, configuration #1 is the best candidate for constructing an antenna array. It has a simple shape and represents the trade-off between high gain and a relatively wide operating range. Therefore, it was chosen for the next step of the research.

### 4. Antenna array generating OAM signal based on the Configuration #1

As it was stated at the beginning of the paper, the main goal of the microstrip antenna development was related to the antenna arrays generating OAM radio signals. Therefore, in the least part of the research, we investigated the antenna array based on the chosen configuration.

At this step, eight antennas of configuration #1 were combined in the array, placed in a circle with the radius $2.5\lambda$ from the array center to the antenna center. The radiators are oriented in a way that provides the ease of feeding, i.e. their tops are directed toward the circle center, and the feeding points...
are located on the outer side (figure 10). The total size of the developed array without connectors is 14.28 mm × 14.30 mm. It is very compact, which is a significant advantage for application in modern mm-wave networks.

![Figure 10](image1)

**Figure 10.** The patch antenna array front (a) and back (b) view.

The array can generate the signals with three states of OAM: +1; 0; -1, and has the realized gain 7.24 dB. The example of E-field intensity and phase for OAM state \( l = +1 \) at the wireless propagation distance of 4\( \lambda \) is shown in figure 11. The spiral phase front of the transmitted signal is clearly observed, which means that the design task is solved.

![Figure 11](image2)

**Figure 11.** The E-field radiation: (a) intensity; (b) phase.

5. **Conclusions**

In this paper we proposed three configurations for the microstrip antenna based on the advanced circular patch for application in the antenna arrays, forming radio signal with the given OAM state. The antenna configurations were calculated via mathematical and computer modeling, and the simulation results are presented. Particularly, return loss \( S_{11} \), VSWR, input impedance, radiation pattern were calculated and analyzed. Based on the comparison of the characteristics of the proposed models, configuration #1 was selected as the best candidate.

The chosen configuration provides the opportunities for miniaturization of the antenna array and, hence, can reduce its implementation costs. Its features allow expanding the possibilities of modern and future communication systems, such as Radio-over-Fiber and Internet of things networks. In total multiplexing by OAM will increase the capacity and noise immunity of these networks along with improving the efficiency of usage and expanding the service area.

6. **References**

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