UDC 621.396(045)
DOI:10.18372/1990-5548.61.14226

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MICROSTRIP ANTENNAS FOR UNMANNED AERIAL VEHICLES APPLICATION

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Abstract**—*The theoretical bases of the development of an microstrip antennas for unmanned aerial vehicles are presented. Antennas characterized by the directed emission, low aerodynamic resistance and mass, possibility to fully fit the unmanned aerial vehicles surface. Antenna system may includes 3-4 sector patch radiators, thin screens in order to depress side and back lobes. Article includes formulas for calculations parameters and characteristics rectangular patch radiators of linear and circular polarization such as resonant frequency, effective dielectric permittivity, patch length and width, input impedance in a feed point, coordinate of coaxial cable connection and patterns in E, H – plane for linear polarization, axial ratio, patch dimensions and bandwidth for circular polarization.*

Index Terms—unmanned aerial vehicle; microstrip antenna; directed radiation.

I. INTRODUCTION

The use of unmanned aerial vehicles in modern times has acquired a global dimension. Unmanned aerial vehicles (UAV's) are used for both military and civil purposes. Communication equipment of UAS's serves for transfer urgent information from the airborne systems and payload equipment (usually video) to the ground, also for reception control signals from the ground station.

II. PROBLEM STATEMENT

The antenna systems must operate at selected frequencies with a bandwidth sufficient to use modern digital and advanced radio technologies, provide electromagnetic compatibility with on-board equipment and operate in selected sectors of the space according to the criteria of quality and secrecy of communication, energy efficiency, acceptable mass and dimensions. Loss of communication in many cases leads to the loss of UAV's.

Most UAV's used in Ukraine are small and very small in the US classification (range up to 100 km, weight up to 10 kg and altitude up to 1500 m). UAV's are not equipped with satellite communication equipment, and the communication range is limited by the line of sight (LoS) and depends on the altitude, radiation power, antenna gain and frequency range. In order to reduce the overall dimensions of the on-board equipment and antenna systems, decimeter and centimeter wave bands are used. The increase in radiation power is accompanied by a sharp increase in the mass of the power amplifiers in the microwave band. Therefore, the achievement of a given communication distance is possible due to the development of the class of on-board antennas, which would compensate the low radiation power by a corresponding gain. Also low aerodynamic resistance, mass and cost limitations must be considered.

For the total isotropic pattern in horizontal plane it is enough to use antenna system with 3–4 sector radiators on the base of microstrip antennas (Fig. 1). Only one radiator operates with the ground control station.

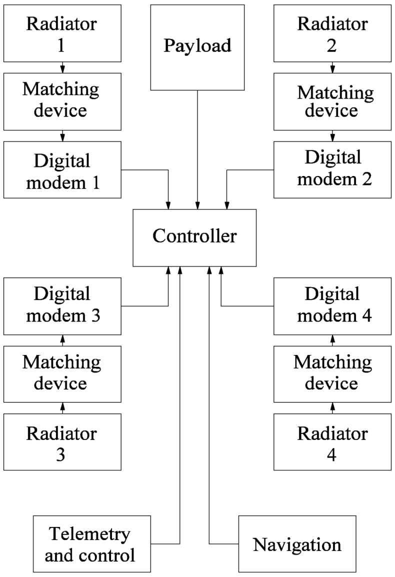

Fig. 1. UAV's communication equipment

III. THEORETICAL BASIS

Figure 2 shows coordinate system and dimensions for determining radiation field of rectangular patch [1].

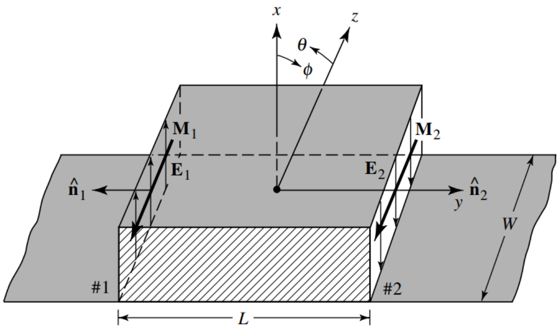

Fig. 2. Coordinate system of an rectangular patch

The resonant frequency f_{nmp} of the antenna depends on the patch dimensions, the thickness of the substrate H and the relative permittivity ε_r [2]

$$f_r = f_{nmp} = \frac{k_{nmp}}{2\pi\sqrt{\varepsilon_r}}, \tag{1}$$

where n, m, p is respectively, the number of the field variations (antinodes) along the x, y, z axes; k_{mnp} is a phase factor

$$k_{mnp} = \sqrt{\left(\frac{m\pi}{W}\right)^2 + \left(\frac{n\pi}{L}\right)^2 + \left(\frac{\rho\pi}{H}\right)^2},$$

W is the width and L is the length of the patch.

Calculation the patch width

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}, \tag{2}$$

where c is the light speed.

The size L for the wave E_{OnO} is equal to or multiple of half wavelength

$$L_n = \frac{nc}{2f_r\sqrt{\varepsilon_r}}.$$

At $n = 1$, the length should be half a wave. However, due to the edge field of the plate, the resonant frequency is slightly lower than the value f_r (1). This effect can be accounted by the use of effective dielectric constant

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \left(\frac{\varepsilon_r - 1}{2}\right)\left[1 + 12\left(\frac{H}{W}\right)\right]^{-0,5}$$

that results in resonant frequency change

$$f_{r.eff} = \frac{k_{nmp}}{2\pi\sqrt{\varepsilon_{eff}}}$$

and change of real patch length [3], [6]

$$\Delta = 0.412H\frac{\varepsilon_{eff} + 0.300\,W/H + 0.262}{\varepsilon_{eff} - 0.258\,W/H + 0.813}.$$

At thin substrate the Δ is negative and the length of the patch decreases

$$L = \frac{\lambda}{2} + 2\Delta. \tag{3}$$

It is generally considered that a microstrip of length L and width W at both ends along the width is loaded on the radiating slots. The radiation conductivity (active input conductivity) of the slot is given by the formula [4]

$$g = \frac{W}{120\lambda}\left[1 - \frac{(k_O H)^2}{24}\right], \tag{4}$$

where $k_O = \frac{2\pi}{\lambda_O}$; λ_O is a wavelength in a free space.

Reactive input conductivity

$$b = 0.01668\frac{\Delta}{H}\frac{W}{\lambda}\varepsilon_{eff}.$$

The input impedance at feed from the patch edge can be approximately defined by the double radiation resistance (4) of the slot

$$R_{e(y=L/2)} = \frac{1}{2g}. \tag{5}$$

The input resistance of the antenna changes from zero in the center of the antenna to the value at the edge of the plate as follows [1]:

$$R_y = R_e \sin^2\left(\frac{\pi x}{L}\right),$$

where $0 \le y \le \frac{L}{2}$ is the distance from the center of the patch along the y-axis.

Coordinate of coaxial cable connection for linear polarization

$$y = \frac{L}{\pi}\arcsin\left(\sqrt{\frac{R_y}{R_e}}\right).$$

Here R_y is equal to wave impedance of coaxial cable and the resistance R_e is refined [4] with comparison by the formula (5)

$$R_e = \frac{1}{2g\left(1+F_g\right)},$$

where $F_g = J_0(l) + \frac{p^2}{24-p^2} J_2(l)$, J_n is Bessel function of the first kind of nth order; $l = k\left(L +_\Delta L\right)$; $p = k_\Delta L$.

Low mass leads to frequent UAV evolutions in space during flight. Therefore, the use of circular polarization should be considered.

The simplest antenna design will be at single feed of almost-square patch (Fig. 3).

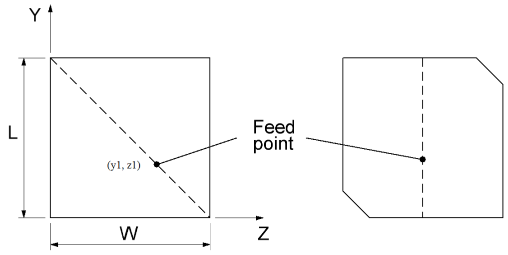

Fig. 3. Geometries of single feed circular polarized patches

At diagonal excitation of almost-square patch the feed point is set as [1], [5]

$$\frac{y1}{L} = \frac{z1}{W}.$$

In Figure 3 the case of right-hand circular polarization is shown. For the left-hand polarization the other patch diagonal is used. Orthogonal oscillations with a phase shift 90° occur at close resonant frequencies. The axial ratio

$$AR = \frac{E_y}{E_z} \approx \frac{k[1-j/(2Q_t)]-k_y}{k[1-j/(2Q_t)]-k_z},$$

where $Q_t = 1/\tan\delta_{eff}$; $\tan\delta_{eff}$ is a dielectric loss tangent; $k_y = \pi/L$; $k_z = \pi/W$.

Patch dimensions is found using

$$L = W(1+1/Q_t).$$

The circular polarized wave is radiated in rather narrow band, which is defined by empirical formula

$$BW_{(\%)} = 12\frac{AR_{(\mathrm{dB})}}{Q_t},$$

where $Q_t \geq 10$.

Considering linear polarization the radiating slots along the width of the patch are at a distance L from each other. The radiating field intensity of the slots are in phase along the normal direction to the patch.

In the E-plane (xoy in Fig. 2), the antenna pattern is determined at an angle $\theta = 90°$ in the range of angle φ change from 0 to 2π, and in the H-plane the angle $\varphi = 0$ and angle θ changes from 0 (direction of axis z) to π.

Under the condition $k_0 H = \frac{2\pi}{\lambda_0} H << 1$ that is usually fulfilled in practice, the antenna pattern in the E-plane is calculated by the formula [3]

$$f(\varphi) = \frac{\sin\left(\frac{k_o H}{2}\cos\varphi\right)}{\frac{k_o H}{2}\cos\varphi}\cos\left(\frac{k_o L_{eff}}{2}\sin\varphi\right), \qquad (6)$$

and in H-plane

$$f(\theta) = \sin\theta \frac{\sin\left(\frac{k_o H}{2}\sin\theta\right)}{\frac{k_o H}{2}\sin\theta} \frac{\sin\left(\frac{k_o W}{2}\cos\theta\right)}{\frac{k_o W}{2}\cos\theta}. \qquad (7)$$

The patterns using (6) and (7) are satisfactorily agree with the results of measurements real antennas with finite screen sizes. The difference is a certain radiation level of real antennas into the hemisphere with angle φ values from 90° to 270° in the E-plane and for negative values of the angle θ in the H-plane.

IV. MODEL DESIGN

Program of microwave device FEKO (method of moments) is used in the model construction. The study of the model was performed by using the substrate with parameters: the thickness 0.001 m, the dielectric loss tangent tan δ =0.0009, effective permittivity δ_{eff}=3. The screen material is copper.

The beamwidth of the patch in the E-plane is sufficient for the communication of UAV with ground control station in vertical plane. At this the patch must be placed so that direction of the maximal radiation will be inclined to the ground.

The number of radiators in horizontal plane depends on the beamwidth in the H-plane. The patch pattern in horizontal plane at $f = 5$ GHz, $2(W \cdot L)$ screen of the substrate and patch dimensions by (2), (3) is in the Fig. 4. This patch can operate in the sector 60º–70º of the horizontal plane. Therefore the number of sector radiators will be 6. This is quite a lot for the UAV of small class. Furthermore the level of back lobe is rather high (about –11 dB from the direction of maximal radiation).

Decreasing the size of the substrate screen to $W(1+2H\varepsilon_{eff})$, $L(1+2H\varepsilon_{eff})$ the main lobe can be expanded to 90º (Fig. 5). At this antenna system will include 4 radiators like in Fig. 1. The level of back lobes is restricted by –17 dB. The gain is equal to 7 dB.

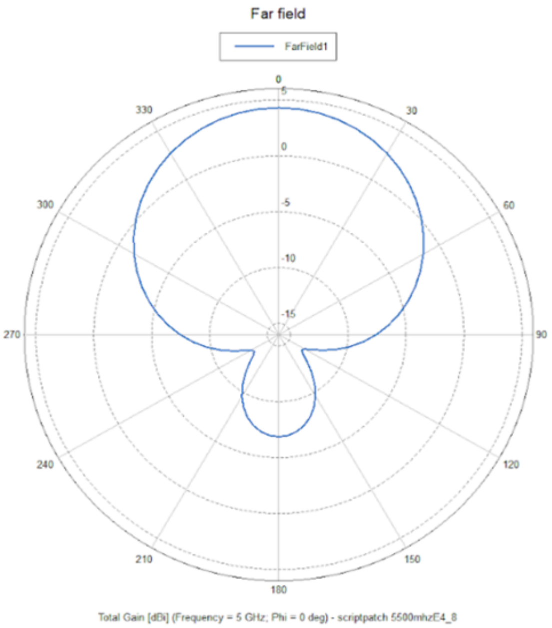

Fig. 4. The rectangular patch pattern mounted on $2(W \cdot L)$ screen

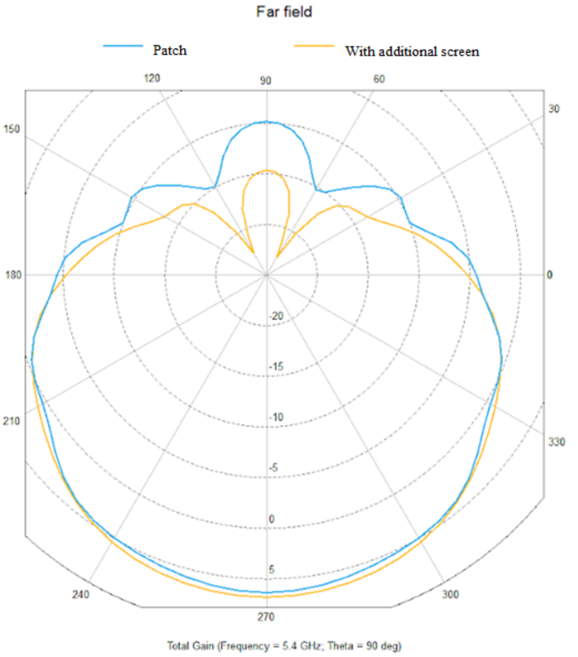

Fig. 5. The patch patterns at defined size of substrate screen and using the same patch with additional screen

A further decrease in the level of the side and back pattern lobes is possible with the help of a screen glued to the UAV body. The microstrip antenna is located at a distance $(0.15-0.25)\lambda$ over the screen. The level of radiation to the back hemisphere diminishes from the – 12 dB at $\varphi = 0°, 180°$ to – 22 dB in sector $\varphi = 45° - 135°$. At a frequency near 5.5 GHz such construction will not cause considerable aerodynamic drag.

V. CONCLUSIONS

Application of the on-board antenna system, including sector radiators instead of antennas isotropic in horizontal plane, permits increase the antenna gain, decrease the radiation power. Additional advantages are spatial secrecy of the communication and possibility to use rotating polarization.

Next work will describe the opportunity to use in antenna system another radiators on the basis of microstrip technology and application of the curved radiators, which corresponds to various surfaces of the UAV body.

REFERENCES

[1] C. A. Balanis, *Antenna Theory Analysis*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2005, 1073 p.

[2] Dottorato Pasquale, "Analysis and Design of the Rectangular Microstrip Antenna for E_{OnO} operating mode," *Microwave Journal*, 2010, October. http://www.microwavejournal.com/articles/12424

[3] A. Milligan Thomas, *Modern antenna design*, John Wiley & Sons, Inc., Hoboken, New Jersey, 2005, 614 p.

[4] R. E. Munson, "Conformal microstrip antennas and microstrip phased arrays," *IEEE Transactions on Antennas and Propagation*, vol. AP-22, no. 1, January 1974, pp. 74–78.

[5] W. F. Richards, "Microstrip Antennas," Chapter 10 in *Antenna Handbook: Theory, Applications and Design* (Y. T. Lo and S. W. Lee, eds.), Van Nostrand Reinhold Co., New York, 1988.

[6] E. O. Hammerstad, "Equations for Microstrip Circuit Design," *Proc. Fifth European Microwave Conf.*, September 1975, pp. 268–272.

Received September 07, 2019.

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Л. В. Сібрук, О. І. Човгун, Д. П. Бондаренко. Мікросмужкові антени для безпілотних літальних апаратів

Представлено теоретичні основи розробки мікросмужкових антен для безпілотних літальних апаратів. Антени характеризуються спрямованим випромінюванням, низьким аеродинамічним опором і масою, можливістю повної відповідності формі поверхні безпілотного літального апарату. Антенна система може включати в себе 3-4 секторні мікросмужкові випромінювачі, екрани для придушення бічних і задніх пелюсток діаграми спрямованості. У статті наведено формули для розрахунку параметрів і характеристик прямокутних випромінювачів лінійної і кругової поляризації, таких як резонансна частота, ефективна діелектрична проникність, довжина і ширина випромінювача, вхідний опір у точці живлення, координати підключення коаксіального кабелю і діаграми спрямованості в Е і Н-плоскостях для лінійної поляризації, радіальне співвідношення, ширина смуги пропускання, розміри близької до квадратної мікросмужкової пластини для кругової поляризації.
Ключові слова: безпілотний літальний апарат; мікросмужкова антена; спрямоване випромінювання.

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Л. В. Сибрук, А. И. Човгун, Д. П. Бондаренко. Микрополосковые антенны для беспилотных летательных аппаратов

Представлены теоретические основы разработки микрополосковых антенн для беспилотных летательных аппаратов. Антенны характеризуются направленным излучением, низким аэродинамическим сопротивлением и массой, возможностью полного соответствия форме поверхности беспилотных летательных аппаратов. Антенная система может включать в себя 3–4 секторные микрополосковые излучатели, экраны для подавления боковых и задних лепестков диаграммы направленности. В статье приведены формулы для расчета параметров и характеристик прямоугольных излучателей линейной и круговой поляризации, таких как резонансная частота, эффективная диэлектрическая проницаемость, длина и ширина излучателя, входное сопротивление в точке питания, координаты подключения коаксиального кабеля и диаграммы направленности в Е и Н -

плоскостях для линейной поляризации, радиальное отношение, ширина полосы пропускания, размеры близкой к квадратной микрополосковой пластины для круговой поляризации.

Ключевые слова: беспилотный летательный аппарат; микрополосковая антенна; направленное излучение.

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Направление научной деятельности: антенны, распространение радиоволн, радиомониторинг, радиосвязь.
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