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Synthesis of a Radiator in the Frequency Range of 0.9…5.8 GHz

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Abstract

Introduction. This work considers the problem of radiator synthesis with the 50-Ohm port at the input in the frequency range of 0.9…5.8 GHz. At the present time, this frequency range is most relevant for the electromagnetic environment analysis, since information exchange with the on-board equipment of unmanned aerial vehicles most often uses this frequency range.

Objective. To synthesize a radiator for an ultra-wideband antenna array in the frequency range of 0.9…5.8 GHz.

Materials and methods. The finite element method of electrodynamics modelling was applied for the synthesis of a broadband radiator using HFSS software tools. The characteristics of the radiator optimised by means of simulation were con-firmed by experimental investigations of the radiator electrodynamic model. Antenna radiation pattern measurements were carried out in an anechoic chamber with standing wave ratio (SWR) and calculated by using a network analyser.

Results. The study proposes a non-analytical method of the parametric optimisation model considering the SWR<2 criterion suitable for use in electrodynamic modelling tools (HFSS, CST, FEKO, etc.). Examples of the optimised model with final values of all geometric parameters of the radiator were reported. The study also presents calculated distributions of the electric field over the antenna, calculated radiation patterns at the extreme frequency points of the operating range (0.9 GHz…5.8 GHz) and the calculated SWR of the model. These results supported the general performances of the antenna under consideration. The radiator model thus produced took simulation and parametric optimisation of the geometry of radiator results into account. The measured main cross-sections of the radiation pattern and SWR of the model were shown.

Conclusion. The paper shows the design of a broadband radiator model in the frequency range of 0.9…5.8 GHz. Machining and a brief comparative analysis of the calculated and measured antenna characteristics were carried out. It demonstrated a good correlation between the calculated and measured radiation patterns and the dependences of the SWR on the frequency. The advantages of the proposed method and designed radiator model were de-scribed. The results of the work are relevant in the areas of observation, direction finding and signals reception from unmanned aerial vehicles.

Key words: ultra-wideband antenna, Vivaldi antenna, microwave range, full-wave electromagnetic simulation

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ORIGINAL ARTICLE

Синтез направленного излучателя в диапазоне 0.9...5.8 ГГц

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Аннотация

Введение. Рассмотрена проблема синтеза направленного излучателя с 50-омным портом на входе, в частотном диапазоне 0.9...5.8 ГГц. Данный диапазон на сегодняшний день является наиболее актуальным для анализа электромагнитной обстановки, так как в этой полосе частот наиболее часто реализуется обмен информацией с бортовой аппаратурой беспилотных летательных аппаратов

Цель работы. Синтез направленного широкополосного излучателя в частотном диапазоне 0.9...5.8 ГГц.

Материалы и методы. Для синтеза широкополосного излучателя используется метод конечных элементов при электродинамическом моделировании в программном средстве HFSS. Характеристики излучателя, оптимизированные на электродинамической модели, подтверждаются с помощью натурных экспериментов на макете излучателя. Измерения диаграммы направленности, проводимые в безэховой камере, и коэффициента стоячей волны (КСВ) осуществляются с помощью анализатора цепей.

Результаты. Предложен неаналитический метод параметрической оптимизации модели по критерию КСВ < 2 удобный для применения в средствах электродинамического моделирования (HFSS, CST, FEKO и др.). Приведены эскизы разработанной оптимизированной модели с указанием итоговых значений всех геометрических параметров излучателя. Представлены снимки расчетного распределения электрического поля на полотне антенны, расчетные диаграммы направленности на крайних частотных точках рабочего диапазона (0.9 ГГц...5.8 ГГц), расчетный КСВ модели. Полученные результаты дают представление об основных характеристиках синтезируемой антенны. По результатам моделирования и параметрической оптимизации геометрии излучателя изготовлен макет антенны. Приведены измеренные главные сечения диаграммы направленности и КСВ макета.

Заключение. В результате представленного исследования разработана модель широкополосного излучателя в диапазоне 0.9...5.8 ГГц, проведено макетирование и краткий сравнительный анализ расчетных и измеренных характеристик антенны, демонстрирующий хорошее совпадение расчетных и измеренных диаграмм направленности и зависимостей КСВ от рабочей частоты. Описаны преимущества предложенного метода и самой модели излучателя. Результаты работы актуальны в задачах наблюдения, пеленгации и приема сигналов от беспилотных летательных аппаратов.

Ключевые слова: сверхширокополосная антенна, антенна Вивальди, СВЧ-диапазон, электродинамическое моделирование

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Introduction. There is a growing interest in ultra-wideband radio systems due to their numerous benefits [1, 2]. These benefits are high resolution and the ability to recognise objects for radar systems, as well as a wide bandwidth and the ability to convert data transmission for radio communication systems.

The development of high-frequency channel elements for ultra-wideband systems requires special approaches which differ significantly from traditional ones. These elements are radiating devices.

The objective of this work is the synthesis of a directional broadband radiator in the frequency range of 0.9…5.8 GHz, with a target parameter in the radiator operating bandwidth. In a narrow sense, the antenna bandwidth is a frequency range where the radiator's standing wave ratio (SWR) does not exceed 2. In present work, the frequency range of 0.9…5.8 GHz was selected since information (telemetry, control, and video data) exchange with the on-board equipment of unmanned aerial vehicles most often uses this frequency range.

In a broad sense, there is an additional requirement for the independence of electrical characteristics (for example, directional properties) from the operating frequency, in addition to the matching requirement in the given frequency range. At the same time, the radiator needs to be compact.

Existing types of broadband radiators. There are no strict criteria for the classification of antennas by bandwidth, however, specialists use the following frequency (ν) parameter differentiations [3]:

$$2\frac{\nu_{\max}-\nu_{\min}}{\nu_{\max}-\nu_{\min}}<0.1$$

stands for the resonant narrowband radiator;

$$2\frac{\nu_{\max}-\nu_{\min}}{\nu_{\max}+\nu_{\min}}<0.15$$

stands for the broadband radiator;

$$\frac{\nu_{\max}}{\nu_{\min}}\geq 5$$

stands for the ultra-wideband (UWB) of frequency-independent radiator.

An additional balancing device in a power supply unit is often used to expand the operating frequency band [4–6]. These measures do not allow a significant frequency band increase, but introduce limitations on the maximum signal power, radiator minimum characteristic dimensions, signal reception and transmission minimum losses, etc. Therefore, when designing a UWB antenna it is reasonable to choose ultra-wideband rather than narrowband radiators.

At the present time, there are several known types of UWB antennas: namely spiral, fractal, log-periodic, as well as Vivaldi antennas.

Fractal radiators have many operating frequency ranges; however, there are large ranges of mismatched frequencies between them. Examples of successful fractal UWB antennas include particular cases designed on the basis of a section of a self-similar geometric figure (for example, spiral and log-periodic antennas). At the present time, fractal forms in radiator synthesis have not been fully studied [7, 8]. Log-periodic antennas are rejected due to the inapplicability of volumetric geometries in the frequency range of 0.9…5.8 GHz. Due to feeder path particularities, printed log-periodic antennas must be implemented by using a 3-layer-board. This significantly complicates the technological process. Furthermore, little research has been carried out into radiators for such high-frequency ranges. For similar reasons, spiral antennas must also be rejected [9].

Vivaldi antenna is a generic name of a class of antennas with different UWB properties. The radiator itself has a popular name about which there can be little argument. However, according to the scientific classification it is a class of printed travelling-wave slot antennas (PTWSA) with an etched slot in the metallisation antenna layer as their radiating part. The first mention of PTWSA dates back to 1979 in the experimental work of Gibson [10]. Various methods for obtaining radiation characteristics of analytical electromagnetic antenna models have been developed and later studied. Thus, profiles with exponential change in width of the gap, Fermat–Dirac profiles, etc., emerged [11–13].

UWB radiator model. At the present time, there is no single simple method for UWB PTWSA synthesis. An analytical method of the PTWSA synthesis has been developed and considered in [3, 14]. The method is based on the multiplicative criterion choice and the further search for geometries that meet it. These methods do not take field distribution in power nodes into account, but they quite accurately describe the fields on the antenna profile and sheet. The analytical approach involves integration of the required output characteristics as functions of antenna sheet geometry [15]. Thus, the analytical task of the PTWSA synthesis is reduced to approximation of the required output characteristics dependencies and further selection of sheet geometry by considering all possible approximations. This calcu-

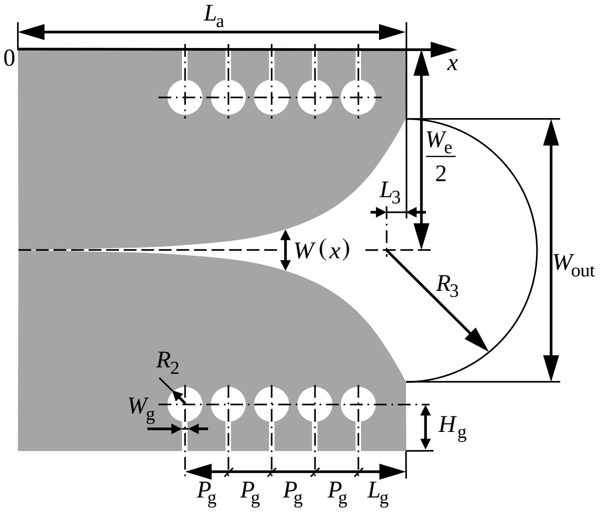

Fig. 1. Scheme of the radiating part of the printed traveling-wave slot antenna

lation method is extremely difficult to apply in practice and in production.

In a certain sense, the PTWSA synthesis method utilising the latest electromagnetic simulation tools (CST studio, HFSS, FEKO, etc.) is less complicated. This method is also based on parametric geometry optimisation. However, it does not require output characteristics analytical approximation, since the antenna geometry is analysed using the finite element method [16].

At the present time, the parametric optimisation method is widely used [17]. Resolution of the Vivaldi antenna synthesis problem begins with the selection of the optimal and general structure of the radiator model.

For the solution described, the structure of the initial PTWSA model is taken from [14] in which certain PTWSA cases are studied in higher frequency bands. The scheme of the antenna radiating part (Fig. 1) has an exponential slot profile $W(x)$. The substrate rectangular profile is supplemented by a phase-correcting lens in a form of a circular sector of a radius R_3. Oscillation circuits in the form of slots with parameters R_2, W_g, located at a distance H_g from the antenna sheet edge are etched on the lateral faces of the model's radiating part, in order to reduce the side radiation level at low frequencies. The shape and number of circuits vary. They are ultimately selected in accordance with the optimal shape of the radiation pattern (RP) at low frequencies, so that there are no unacceptable resonant effects which delay or modulate the signal when the antenna operates in pulsed mode [14]. In this case, RP at upper frequencies remains practically unchanged.

A microstrip-to-slot transition (Fig. 2) [3], which can be implemented on a printed circuit board common with the PTWSA, is chosen as a PTWSA power node. The power line metallisation is on the dielectric substrate reverse side with respect to the radiator sheet.

The length section L_{tr} (рис. 2) Fig. 2) is a step-up transformer between the 50Ω line and capacitor of a circular sector of a radius R_5.

The power line and radiating part are simulated and optimised separately. Variable parameters of the model (Fig. 1, 2) are W_e, L_a, W_{in}, W_{out}, R_1, R_2, R_3, L_3, L_g, P_g, W_g in the radiating part (Fig. 1), R_4, R_5, $W_{f\,in}$, $W_{f\,out}$, L_{tr}, L_s, and the aperture angle ψ and circular sector orientation ξ in the power line (Fig. 2). The maximum half-length and wave-

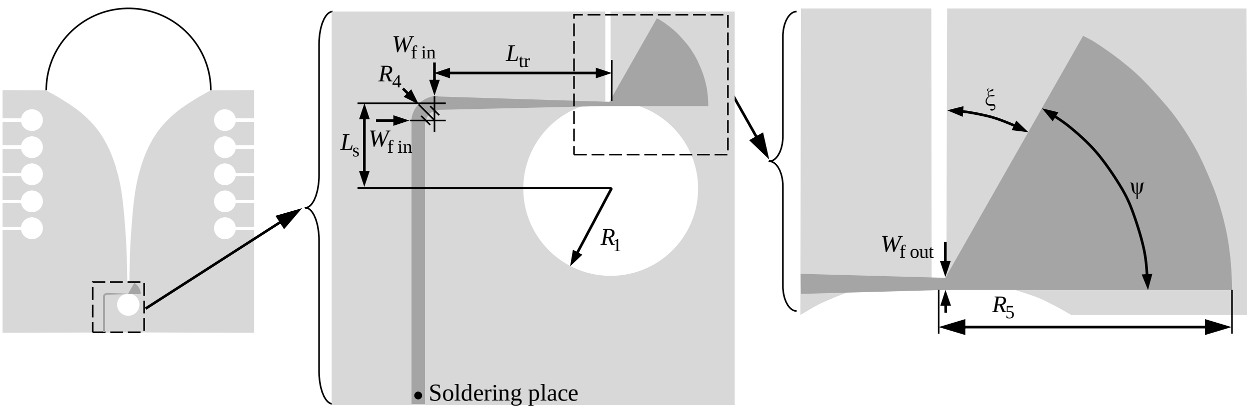

Fig. 2. Power node of the printed traveling-wave slot antenna

lengths in the operating frequency range are selected as the initial antenna dimensions W_e, L_a, respectively. The value W_{out} is selected to be equal to the sheet width. The initial value of the slot width W_{in} is taken to be equal to the 50Ω asymmetric microstrip line width for the dielectric used (0.508 mm thick Rogers RO4003C material).

Parametric optimisation of the PTWSA model is carried out in several iterations by means of electromagnetic simulation using the finite element method. The output characteristics are calculated for all possible variations of the model parameters, in order to determine optimal parameters values in the given ranges. The set of parameters when the area under the SWR graph is minimal in the operating range, is the optimal set of the current iteration. The variation interval of each of the parameters ceased to vary when the parameter current optimal value is inside the interval, but not at its edge. Further parameter optimisation is carried out by the bisection method, so long as satisfactory SWR changes are significant.

Results. The following results were obtained for model optimisation according to the SWR < 2 criterion in the entire range and considering the minimum dependence of the directional properties on the frequency:

$$W_e = 252 \text{ mm}, \; L_a = 245 \text{ mm}, \; W_{in} = 0.35 \text{ mm},$$

$$W_{out} = 167 \text{ mm}, \; R_1 = 7 \text{ mm}, \; R_2 = 11 \text{ mm},$$

$$R_3 = 84 \text{ mm}, \; R_4 = 1.2 \text{ mm}, \; R_5 = 7.8 \text{ mm},$$

$$L_3 = 8 \text{ mm}, \; L_g = 29.5 \text{ mm}, \; P_g = 27 \text{ mm},$$

$$W_g = 3 \text{ mm}, \; W_{f\,in} = 3 \text{ mm}, \; W_{f\,out} = 0.35 \text{ mm},$$

$$L_{tr} = 13.9 \text{ mm}, \; L_s = 6.8 \text{ mm}.$$

The resulting field distributions over the antenna aperture for the average frequency of the range at

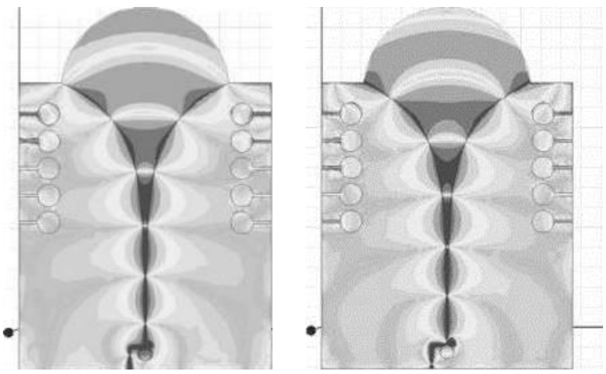

Fig. 3. Field distribution over the antenna aperture at a frequency of 2.4 GHz for two time moments (simulation)

Antenna calculated characteristics after optimization

Frequency, GHz	Maximum gain, dB	Radiation pattern width, …°	
		E-plane	H-plane
0.9	8.4	60	114
2.4	9.0	66	44
5.8	10.9	72	32

two-time moments are shown in Fig. 3. Antenna characteristics calculated after optimisation are shown in the table.

The PTWSA model based on the simulation and optimisation results is thus obtained. (Fig. 4).

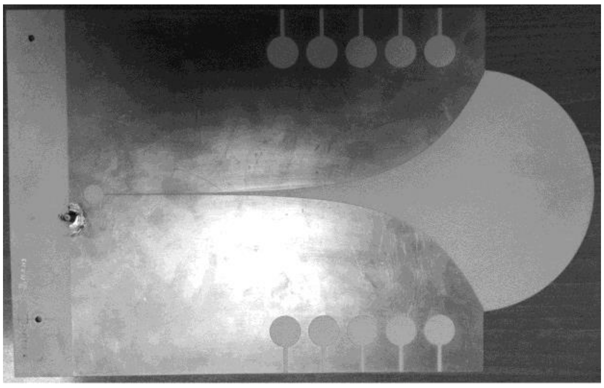

Fig. 4. Model of the printed traveling-wave slot antenna

The results of measuring the radiation pattern of the model in an anechoic chamber and calculated values of the normalised RP (NRP) *D* are presented in Fig. 5. The antenna gain values at the range cut-off frequencies are calculated by considering the NRP measurements. They are 9.8 dB at a frequency of 0.9 GHz and 13.9 dB at a frequency of 5.8 GHz.

The results of the antenna SWR calculation and measurements are shown in Fig. 6. These results fully satisfy the optimisation criterion.

Discussion. In the electromagnetic simulation, an ideal 50Ω power line connects with the microstrip-to-slot transition. The real model differs from the ideal model by the RFS-50-751FA connector presence at this point, introducing its own mismatch resulting in the slight SWR curve difference in the high-frequency region.

The dielectric lens barely affects the phase front shape (Fig. 3). This is due to the fact that the model parameters are optimised according to the SWR < 2 criterion without additional restrictions. Thus, ceteris paribus, the lens can be excluded to reduce the antenna size. The lens parameters should be optimised separately to optimise the phase front shape, since the lens shape weakly affects the antenna matching. Fig. 3

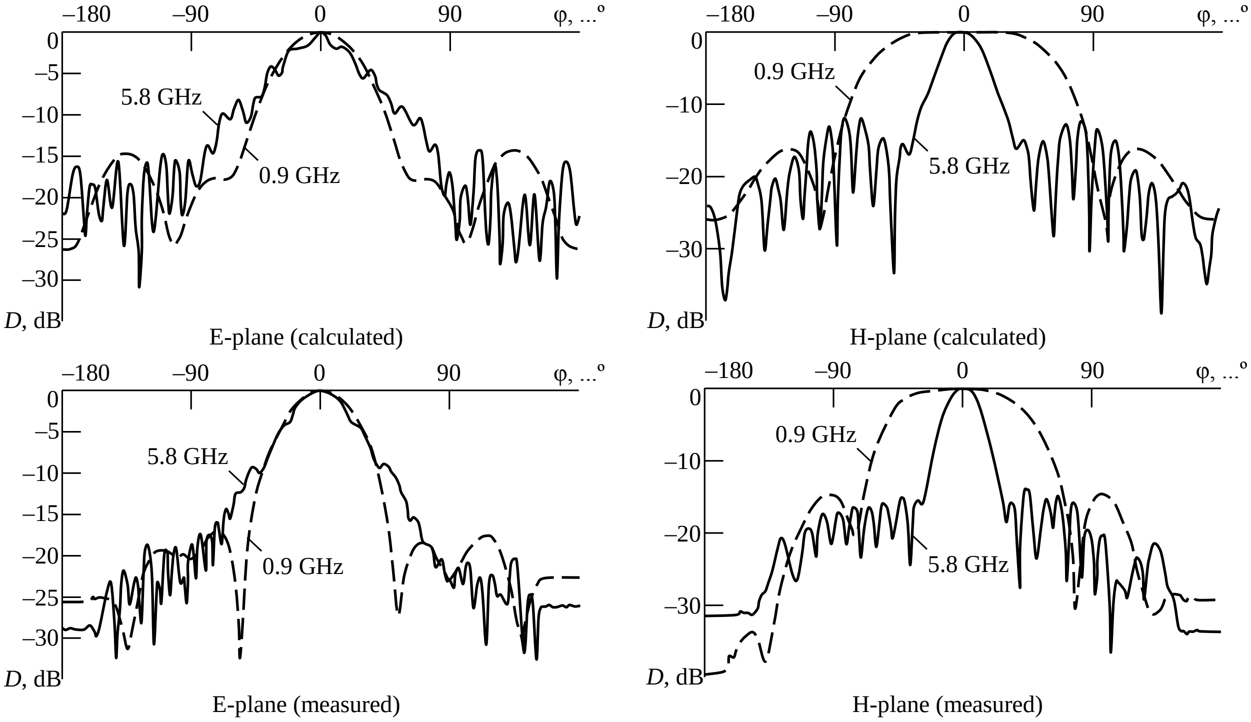

Fig. 5. Experimental normalized radiation patterns of the radiator model at the cutoff frequencies

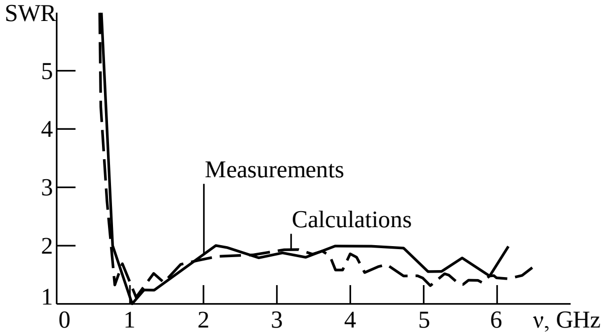

Fig. 6. Antenna matching characteristics

shows the nodes and antinodes of the wave propagating along the antenna sheet which indirectly indicates radiator conformity at the middle frequency of the range.

The maximum difference between the directivity and antenna gain (see table) in the operating frequency range is observed at a frequency of 5.8 GHz. Thus, the minimum antenna efficiency is 10.9–13.9=–3 dB or about 50%. This is a relatively high efficiency for a printed antenna with a characteristic sheet size of 1–6 wavelengths, depending on the selected frequency.

Fig. 5 shows that antenna maintains the radiation directivity in the operating range. The main lobe width in the H-plane decreases with the frequency increase, and the main lobe width in the E-plane is frequency independent. The calculated RPs are wider than those measured due to the differences between the simulated model and real model (presence of the connector in the power line and imperfectly flat front of incident radiation in the anechoic chamber).

The measurements carried out on the designed PTWSA model demonstrate similarities with the results of non-analytical synthesis method of UWB radiator based on the given structural model. The proposed method is convenient for practical use in engineering and is reliable for the given UWB radiator structural model. The antenna is inexpensive and can be easily reproduced

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