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Two-Frequency Operating Mode of Antenna Arrays with Radiators of Clavin Type and Switching Vibrator and Slot Elements

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Abstract—The possibility of application Clavin type radiators in combined two-frequency antenna arrays with diode switching of vibrator and slot elements is validated. The conventional Clavin elements with passive monopoles operating at the main frequency and two active monopoles operating at the alternative frequency are used as the combined array radiator. Radiation fields of combined arrays at both frequencies are analyzed. It is shown that the alternative wavelength should not exceed the main wavelength by more than 25%.

1. INTRODUCTION

One of the important avionics problems is creation of integrated systems combining several functions, such as radio navigation, communication, and radar. The possibility of creating scanning antenna arrays with several beams formed at different frequencies is quite essential for the problem [1, 2]. The aperture of combined antenna arrays usually contains two types of radiators, operating at different wavelengths [2]. The integration of multi-frequency radiators into the antenna array aperture may lead to a significant interaction between the radiators of different sub-bands, which, in turn, may cause specific distortions of directivity of multi-frequency antenna arrays. First of all, this concerns antenna gain decrease due to the power loss in radiators of other sub-bands and origination of additional side lobes [2]. The main goal of combined antenna array development consists in avoiding such distortions as much as possible.

The time division switching of antenna array operating modes can be carried out by high-speed semiconductor diode. Electrically controlled microwave switches were proposed more than fifty years ago [3, 4]. The switches have the following properties: a relatively low control power, good compactness, low losses, high operating speed, wide passband, long lifetime, and high reliability. The switches can be built by using semiconductor diodes, including uncased p-i-n diodes which can provide compromises for switching devices operating in the decimeter and centimeter wavelength with pulsed power up to several kilowatts. Of course, complex combined array elements, in which a structural part of the main radiator isolated by diode switches, can be used as an alternative radiator. This is quite natural and most effective for combined antenna arrays.

One of the known combined radiators is the Clavin element consisting of a narrow slot cut in an infinite screen and two identical passive vibrators (monopoles) of fixed length placed on both sides of the slot at specified distances from the slot center [5–8]. The slot radiates into upper half-space over the screen. The RPs (radiation patterns) of the Clavin antenna element with perfectly conducting monopoles in E- and H-planes were shown to be almost identical [5–7]. The influence of the electric lengths of impedance monopoles and the distance between the Clavin type elements was analyzed under conditions that the level of lateral radiation in the E-plane, and the difference in the widths of the RP

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in main planes at the level of $-3\,\mathrm{dB}$ was taken into account [9, 10]. However, application of a Clavin radiator in combined antenna array has not been studied. The paper is aimed at the solution of this problem.

2. COMMUTATION MODES OF CLAVIN RADIATORS IN ANTENNA ARRAYS

Consider the structure of Clavin type vibrator-slot radiator shown in Fig. 1. The slot cut in an infinite perfectly conducting screen with center located at the origin of a rectangular coordinate system (x, y, z) radiates into half-space with material parameters $(\varepsilon_1; \mu_1)$ over the screen. Two asymmetric vibrators (monopoles) are placed in the plane $\{y0z\}$ at distances y_{d1} and y_{d2} from the slot axis. The vibrator and slot lengths are L_1, L_2, and $2L_3$, and the vibrator radii and slot width are r_1, r_2, and d. The structural elements of radiator will be analyzed in approximation thin linear radiators: $\frac{r_{(1,2)}}{L_{(1,2)}} \ll 1$, $\frac{r_{(1,2)}}{\lambda_1} \ll 1$, $\frac{d}{2L_3} \ll 1$, $\frac{d}{\lambda_1} \ll 1$ (λ_1 is the wavelength in the external medium).

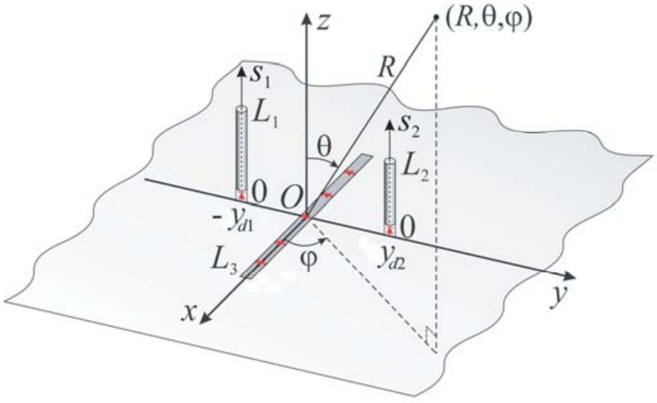


Figure 1. The geometry of the Clavin vibrator-slot radiator.

Consider the Clavin structure with perfectly conducting vibrators as a radiator of combined antenna array. As in [5–7], we will assume that following parameters of the radiator are used: vibrator lengths $L_1 = L_2 = L_v$, radii $r_1 = r_2 = r_v$, and displacements $y_{d1} = y_{d2} = y_v$. For the convenience of further analysis, we redefine $2L_3 = 2L_{sl}$. For definiteness, we also assume that the slot cut in the end wall of the rectangular waveguide adjacent to the screen is excited from the lower half-space by the waveguide wave [11]. The waveguide node intended for slot excitation ensures resonant tuning of the combined radiator operating in the two-dimensional flat array shown in Fig. 2, where the origin of rectangular coordinate system coincides with the antenna array center. The array consists of several rows of vibrator-slot radiators. The distance between adjacent rows of radiators is d_y; the distance between the phase centers of the radiators located in the row is d_x; the number of rows is N_y; and the number of radiators in a row is N_x. We will introduce the spherical coordinate system whose polar axis coincides with the axis $\{0z\}$, and the angle φ is counted out from the axis $\{0x\}$. It is quite clear that the monopoles have electrical contact with the metal screen.

Two groups of p-i-n diodes, marked as shown in Fig. 1 by the red color, are included in the design of the combined array radiator. The diodes of the first group are evenly distributed over the slot aperture so that one diode is obligatorily placed in the slot center. If the diodes of this group are in the OFF state, the electromagnetic field radiation passes through the slot, and the combined radiator operates in the common mode. If these diodes are in the ON state, the slot aperture is shunted; therefore, it can be considered to be metallized. Synchronization of ON command for the diodes and OFF command controlling the power supply to the waveguide excitation node is required for the correct radiator operation. Thus, if the slot diodes are in the OFF state, the antenna array aperture operates at the main frequency as shown in Fig. 2.

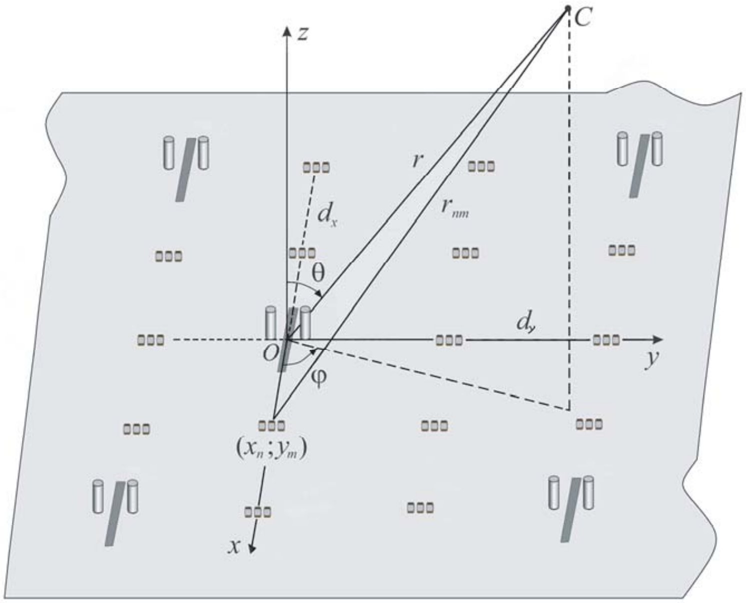


Figure 2. The antenna array aperture operating at the main frequency.

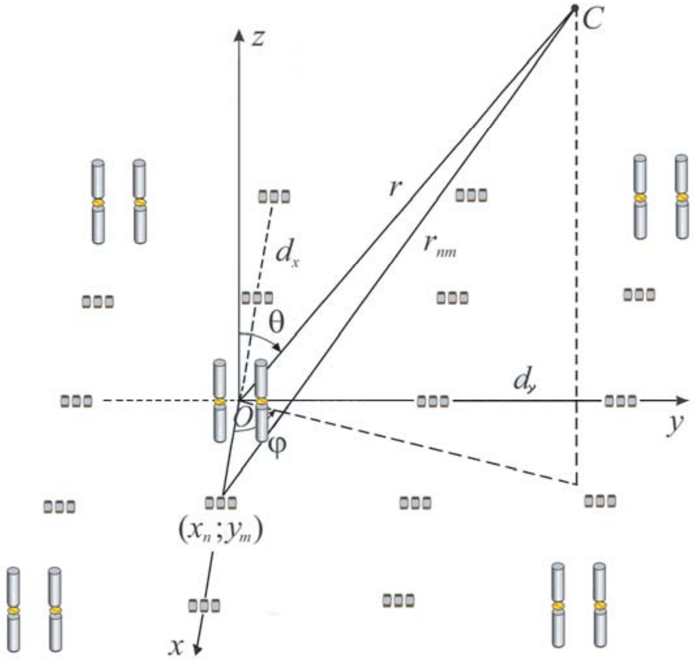


Figure 3. Virtual antenna aperture operating at the alternative frequency.

The diode switches intended for controlling power applied to the monopoles are also attached to the monopole bases to isolate the excitation nodes and monopoles (Fig. 1). If the diodes are in the OFF state, the monopoles operate in the passive mode ensuring the functioning of the combined emitter in the main mode. If the diodes are in the ON state, the monopoles are connected to the excitation nodes allowing operation in the active mode. It is quite clear that the synchronization ON and OFF commands for the vibrator diodes and monopole excitation generators are also required. In addition, the design of excitation nodes must guarantee resonant monopole tuning taking into account their mutual influence. Thus, if all diode switches in the slot and vibrators are in the ON state, the antenna array aperture shown in Fig. 3 operates at the frequency of vibrator excitation. It should be noted that the virtual aperture shown in Fig. 3 is built under conditions that the symmetrical vibrators are active; the perfectly conducting screen is absent; and the mirror images of monopoles are not taken into account.

3. RADIATION FIELDS OF THE COMBINED ANTENNA ARRAY

The radiation fields of the combined antenna array will be analyzed under the assumption that it radiates into free half-space ($\varepsilon_1 = 1; \mu_1 = 1$); therefore, the wave number $k = 2\pi/\lambda$, where λ is the wavelength in free space. First, let us characterize the radiation fields of single combined Clavin radiator (Fig. 1) based on well-known literature data. The combined antenna element proposed in [5, 6] consists of two identical perfectly conducting monopoles symmetrically located at the distance $y_v = 0.086\lambda$ relative to the slot axis. Clavin has experimentally shown that similar RPs in the main planes can be obtained if the vibrators and slot dimensions are $L_v = 0.375\lambda$ and $2L_{sl} = 0.5\lambda$. The optimal radiator parameters, $L_v = 0.365\lambda$ and $y_v = 0.065\lambda$ obtained based on the solution of external electrodynamics problem in [7], slightly differ from those established by Clavin. These parameters are achieved due to the lower radiation level along the screen plane than that obtained in [5]. The simulation results obtained in [9] have shown that there exist several pairs of parameters L_v/λ and y_v/λ for which the shapes of radiation patterns (RPs) can differ even if the level of lateral radiation is constant. As a result of complex simulation [9], it is also found that the requirement of the RPs similarity in the main planes can be satisfied if $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ with the level of lateral radiation $-20\,\mathrm{dB}$ and $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ with the level $-31\,\mathrm{dB}$. Note that the RPs have similar widths in the first case, while the similar RPs with the lowest levels of lateral radiation are observed in the second case.

Analytical formulas applicable to simulation of the vibrator-slot structure (Fig. 1) are obtained by the authors based on the method of induced electro-magneto-motive forces (EMMF) [9, 10]. Consider the monochromatic excitation of the combined radiator by a plane wave when the fields and currents depend on time t as $e^{i\omega t}$ (ω is the circular frequency). In a spherical coordinate system (R, θ, φ), the electric field of the radiator in the far zone ($R \gg \lambda$) can be presented as [9]:

$$\vec{E}(\theta,\varphi)=\frac{ik^2e^{-ikR}}{\omega R}\left[\vec{\theta}^0\sin\theta\left(\tilde{E}_1e^{-iky_v\sin\theta\sin\varphi}+\tilde{E}_2e^{iky_v\sin\theta\sin\varphi}\right)+\left(\vec{\varphi}^0\cos\theta\cos\varphi+\vec{\theta}^0\sin\varphi\right)2\tilde{E}_{sl}\right], \tag{1}$$

where $\vec{\theta}^0$ and $\vec{\varphi}^0$ are unit vectors,

$$\begin{aligned}\tilde{E}_{1(2)} &= \frac{2J_{1(2)}}{k\left(1-\cos\theta\right)^2}\left[\cos\left(kL_v\cos\theta\right)\sin\left(kL_v\right)-\sin\left(kL_v\cos\theta\right)\cos\left(kL_v\right)\cos\theta\right]\\ &\quad -2L_v\cos\left(kL_v\right)\frac{\sin\left(kL_v\cos\theta\right)}{kL_v\cos\theta},\end{aligned} \tag{1a}$$

and

$$\begin{aligned}\tilde{E}_{sl} &= \frac{2J_{sl}}{k-k(\sin\theta\cos\varphi)^2}\left[\cos(kL_{sl}\sin\theta\cos\varphi)\sin(kL_{sl})-\sin(kL_{sl}\sin\theta\cos\varphi)\cos(kL_{sl})\sin\theta\cos\varphi\right]\\ &\quad -\frac{2\cos(kL_{sl})\sin(kL_{sl}\sin\theta\cos\varphi)}{k\sin\theta\cos\varphi}.\end{aligned} \tag{1b}$$

Equation (1b) is obtained under the assumption of symmetrical slot excitation. The complex amplitudes of electric currents $J_{1(2)}$ on monopoles are determined under the condition of predefined amplitude of slot magnetic current [9, 10] obtained as the rigorous solution of the problem taking into account the mutual influence between the vibrators and slot.

At the main frequency, the H-plane ($\varphi = 0°$) RP of the Clavin radiator according to Equation (1) has only the E_φ component which coincides with the single slot RP since $J_1 = -J_2$. The E-plane RP has only the E_θ component, and variation of the monopole currents makes it possible to approximate its shape to the H-plane RP. At the alternative frequency, when the slot is "metallized", and the vibrators are in an active mode, the expression for the electric field of the radiator is simplified to

$$\vec{E}(\theta,\varphi)=\frac{2ik^2e^{-ikR}\sin\theta}{\omega R}\tilde{E}_{1(2)}\cos\left(ky_v\sin\theta\cos\varphi\right)\vec{\theta}^0, \tag{2}$$

where the vibrator currents are assumed to be equal ($J_1 = J_2$).

When RP of the single Clavin radiator defined by Equations (1)–(2) is known, the total radiation field of the antenna array $\vec{E}(r, \theta, \varphi)$ can be defined as the sum of the radiation fields of each element, taking into account the amplitudes and phases of these fields in the observation point $C(r, \theta, \varphi)$. Assuming that all radiators in the nodes of plane arrays shown in Fig. 2 and Fig. 3 are similar, we can write

$$\vec{E}\left(r,\theta,\varphi\right)=\sum_{n=1}^{N_x}\sum_{m=1}^{N_y}\frac{e^{-ikR_{nm}}}{R_{nm}}\vec{E}_{nm}(\theta,\varphi). \tag{3}$$

It should be recalled that all combined emitters in the arrays are assumed to be resonantly tuned by selecting either their intrinsic parameters or the array parameters, d_x/λ and d_y/λ, which allow us to compensate the mutual influence between the radiators. When the radiators of periodic antenna array are characterized by equal current amplitudes, the double summation in Equation (3) can be replaced by the normalized array factor [1]

$$\vec{E}\left(r,\theta,\varphi\right)=\frac{\vec{E}(\theta,\varphi)}{N_xN_y}\cdot\frac{\sin\left[\dfrac{N_x}{2}\left(kd_x\sin\theta\cos\varphi-\psi_x\right)\right]}{\sin\left[\dfrac{1}{2}\left(kd_x\sin\theta\cos\varphi-\psi_x\right)\right]}\cdot\frac{\sin\left[\dfrac{N_y}{2}\left(kd_y\sin\theta\sin\varphi-\psi_y\right)\right]}{\sin\left[\dfrac{1}{2}\left(kd_y\sin\theta\sin\varphi-\psi_y\right)\right]}, \tag{4}$$

where ψ_x and ψ_y are the phase shifts between the currents of neighboring radiators in a row along the $\{0x\}$ axis, and of neighboring radiators in a row along the axis $\{0y\}$.

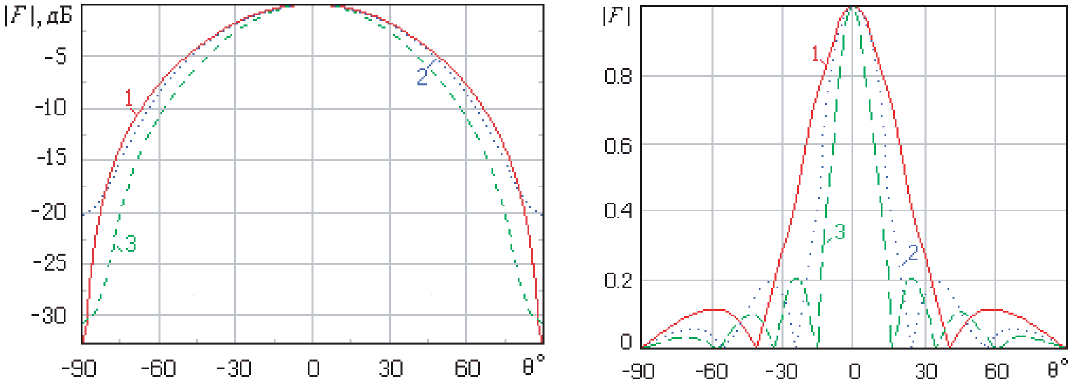
At the main frequency, the maximum of RP of the single Clavin radiator (Fig. 1) defined by Equation (1) is directed along the $\{0z\}$ axis. Since monopoles of the Clavin radiator are passive, the amplitudes and phases should be related to the magnetic current in the slot. As follows from physical considerations, the normal (transverse) radiation mode of the antenna array consisting of Clavin radiator (Fig. 2) can be achieved if $\psi_x = \psi_y = 0$, i.e., with the in-phase operation of the slotted elements. The form of array factor will be kept invariable in any plane ($\varphi = \text{const}$) passing through the $\{0z\}$ axis. Besides, the forms of amplitude RPs in the H- and E-planes do not depend upon the number of radiators in a row N_y and the number of rows N_y.

At the alternative frequency, the radiator of the antenna array (Fig. 3) can be presented by the two monopoles excited by the current of equal amplitudes. In this case, the phase shifts of the fields radiated by the adjacent radiators in Equation (4) should be taken into account relative to phase centers monopole pairs. Moreover, from physical considerations it follows that the regime of axial radiation for the array operating at this mode can be realized under the conditions $\psi_x = kd_x$ and $\psi_y = kd_y$.

4. NUMERICAL RESULTS

The analysis of radiation fields of combined antenna arrays will be carried out based on the simulation results of RP for combined structures presented in Fig. 2 and Fig. 3. The normalized RPs of single Clavin radiator with parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ calculated by Equation (1) are presented in Fig. 4(a). As can be seen, the H-plane RPs calculated with parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ and $L_v = 0.3\lambda$, $y_v = 0.086\lambda$ coincide (curve 1 in Fig. 4(a)), while the E-plane RP calculated with parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ (curve 2) is closer to H-plane RP than E-plane RP calculated with $L_v = 0.3\lambda$, $y_v = 0.086\lambda$ (curve 3). Therefore, only parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$ will be used in the further simulations of combined vibrator-slot structure operating at the main frequency.

Simulation of antenna array fields at the main frequency is carried out under conditions that the array periods $d_x = d_y = \lambda/2$ and phases $\psi_x = \psi_y = 0$. This selection minimizes the mutual influence between the antenna array elements [1]. The normalized RPs in the H-plane obtained by using Equation (4) are presented in Fig. 4(b) for the following configuration: $N_x = N_y = 3$ (curve 1), $N_x = N_y = 5$ (curve 2), and $N_x = N_y = 7$ (curve 3). Simulation results have also shown that the array RPs in the E-plane and H-plane coincide with good accuracy for an arbitrary number of radiators in the array. As expected, we can state based on the well-known electrodynamic principles that the maximum of the RP is oriented normal to the screen plane;the main directional lobes of the RP become narrower; and the number of sides lobes increases if the number of radiators is increased.



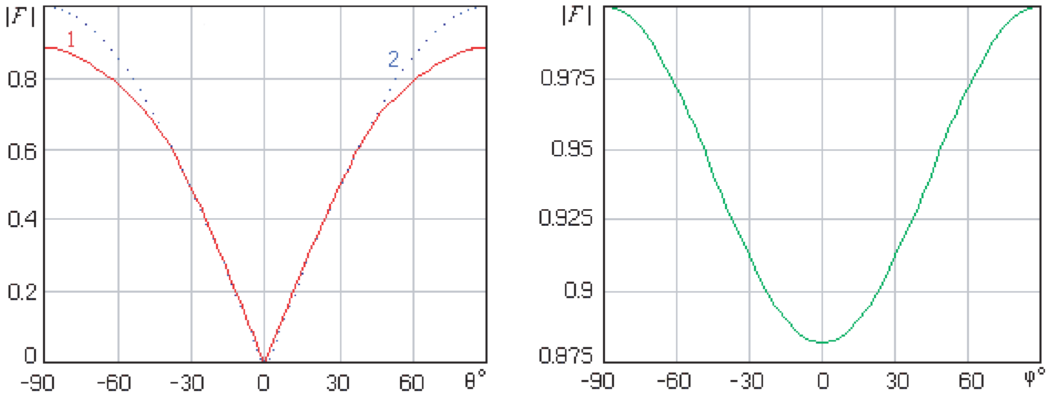
(a) (b)

Figure 4. The RPs of radiating structures at the main frequency: (a) single Clavin element: 1 — in H-plane with parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$; 2 — in E-plane with parameters $L_v = 0.3125\lambda$, $y_v = 0.086\lambda$, 3 — in E-plane with parameters $L_v = 0.3\lambda$, $y_v = 0.086\lambda$; (b) array of Clavin elements: 1 — $N_x = N_y = 3$, 2 — $N_x = N_y = 5$, 3 — $N_x = N_y = 7$.

At the alternative frequency, the two identical active monopoles operate as a single radiator (Fig. 3), whose physical location in the array stays is unchanged. Since the electric lengths of the array periods d_x and d_y are changing due to transition to the alternative frequency and differ from $\lambda_a/2$, the resulting phase shifts should be compensated by some or other method. When such compensation is achieved, the directions of the RP maxima for the single radiator and array coincide. The specified compensation can only be achieved by using the phase shifters in the vibrator transmission lines. Since technical possibilities for implementing such phase shifters are quite limited, the main and alternative frequencies should be fairly close to each other. On the other hand, the optimal operating wavelength λ_a of the vibrator radiator is achieved if the monopole length is $L_v = 0.25\lambda_a = 0.3125\lambda$. Therefore, the alternative frequency should be selected from the wavelength band $\lambda \leq \lambda_a \leq 1.25\lambda$.

The results of numerical simulation are obtained at the alternative wavelength $\lambda_a = 1.1\lambda$ with the combined radiator parameters, $L_v = 0.284\lambda_a$ and $y_v = 0.078\lambda_a$. The normalized E-plane ($\varphi = \pi/2$) and H-plane ($\varphi = 0$) RPs are presented in Fig. 5(a) by curves 1 and 2.

As can be seen from Fig. 5(a), the maximum RP of radiator consisting of two in-phase monopoles is directed in the screen plane ($\theta = \pm 90°$) which is quite different from that of the Clavin element at the main frequency (Fig. 4(a)). The field amplitude in the plane $\theta = \pm 90°$ as a function of angle φ

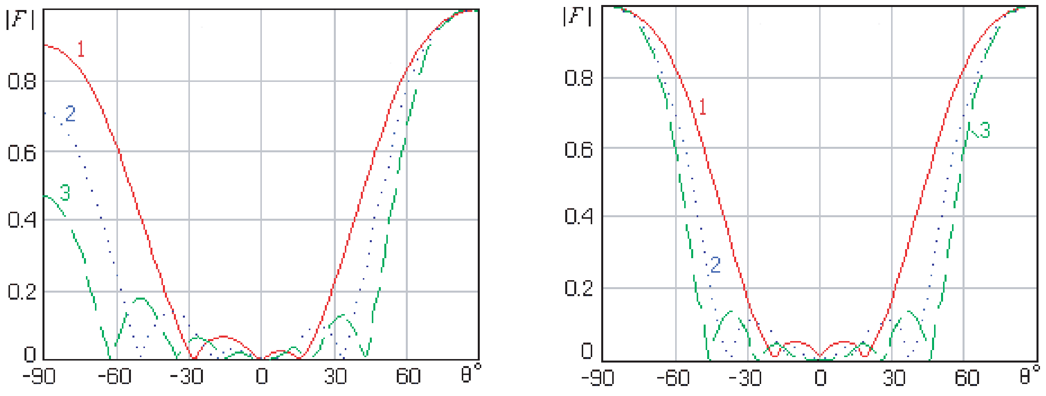


(a) (b)

Figure 5. The RPs of two active monopoles with parameters $L_v = 0.284\lambda_a$ and $y_v = 0.078\lambda_a$ at the alternative frequency: (a) 1 — in E-plane ($\varphi = \pi/2$), 2 — in H-plane ($\varphi = 0$); (b) in plane $\theta = \pm 90°$.

becomes uneven due to displacements of the monopoles along the axis y at the distance $y_v = 0.078\lambda_a$ (Fig. 5(b)). The smallest amplitude is observed in the H-plane ($\varphi = 0°$), and it is lower by 12% than the E-plane amplitude with ($\varphi = 90°$).

If the simulation of antenna array fields based on Equation (4) is carried out at the alternative frequency, the array periods are $d_x = d_y = \lambda/2 = \lambda_a/2.2$, and the parameters are $\psi_x = \psi_y = 0.91\pi$. The simulated H-plane RPs of square antenna arrays are shown in Fig. 6(a) for the arrays with $N_x = N_y = 3$ (curve 1), $N_x = N_y = 5$ (curve 2), and $N_x = N_y = 7$ (curve 3). It is shown that the E-plane RPs are similar to the H-plane RPs represented in Fig. 6(a) for the corresponding number of array elements. It should be noted that the E-plane RPs are similar to the H-plane RPs shown in Fig. 6(a) for identical number of array radiators. Besides, the field amplitudes decrease in directions $\theta = \pm 90°$. The RPs in both planes are asymmetric relative to the direction $\theta = 0°$ due to the phase mismatching between the radiators. If the number of radiators is increased, and hence, phase errors in the observation point are accumulated, the skew of the RP increases. The phase compensations, ensuring equality $\psi_x = \psi_y = \pi$ eliminates the RP asymmetry (Fig. 6(b)). The maxima of all RPs shown in Fig. 6 are oriented along the screen plane; the width of main lobes decreases; and the number of side lobes increases if the number of radiators is increased.



(a) (b)

Figure 6. RPs of the antenna arrays with different number of radiators at the alternative frequency: 1 — $N_x = N_y = 3$, 2 — $N_x = N_y = 5$, 3 — $N_x = N_y = 7$. (a) Without phase compensation; (b) with phase compensation.

The simulation results for other ratios λ_a/λ from the interval $\lambda \le \lambda_a \le 1.25\lambda$ have confirmed the validity of the approach for obtaining field characteristics of the antenna array with the Clavin type radiators.

5. CONCLUSION

Application of Clavin type vibrator-slot structures as radiators in combined dual-frequency antenna arrays with diode switching of the slot and vibrator elements is proposed. The possibility of their application is justified by the results of numerical simulations of radiation fields for both isolated structures and periodic planar array of such radiators. Conventional Clavin elements with passive monopoles are used as the combined radiator at the main frequency, and the pairs of active monopoles are used at an alternative frequency under the condition that the external apertures of the slots are "metallized". The models of antenna structures have been developed in the framework of the electrically thin linear radiator approximation under the condition of monochromatic excitation of the structure.

It has been established that operating wavelength of alternative frequency mode should be selected so that it does not exceed the main mode wavelength more than 25%. The radiation fields of combined arrays, whose maxima are oriented normal to its aperture at the fundamental frequency and along the lattice plane at the alternative frequency, are analyzed under conditions that the above limitations are taken into account.

Thus, the described process of the radiation fields formation by the antenna structures allows us to use the combined arrays with diode switching both for horizontal survey of half-space at the alternative frequency and for azimuthal survey at the main frequency. It should be noted that the operating wavelengths of the main and alternative modes of antenna array can coincide.

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