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# MINIATURIZED ANTIPODAL VIVALDI ANTENNA BASED ON MAGNETODIELECTRIC MATERIALS

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Miniaturization of antipodal Vivaldi antenna (AVA) based on high dielectric constant and magnetodielectric ferrite materials is studied. The basic parameters of antipodal Vivaldi antenna based on high dielectric and magnetodielectric materials (MDM) are compared. To miniaturize the size of the antenna by a higher factor, MDM ferrite with paremeters $\varepsilon_r = \mu_r = 8$ is used. The analysis shows that MDM based Vivaldi antenna surface is minimized by a factor of 4 compared to that of air-based Vivaldi antenna. The sizes of AVA are $120 \times 120 \times 1$ $(mm)$.

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***Keywords*:** miniaturization, antipodal Vivaldi antenna, electrically small antenna, ultrawideband antenna, magnetodielectric material, ferrite.

**Introduction.** Recent wireless devices demand wide bandwidth, high data rate, and more capacity. Due to the rapid development of wireless communication, ultra-wideband (UWB) antennas/systems are becoming highly attractive in many wideband applications such as broadband wireless communications, UWB interference and imaging systems [1]. Vivaldi antennas which are also called exponential tapered slot antennas were introduced as a new class of UWB antenna. It's linearly polarized and can operate at wide bandwidth with high and constant gain [2, 3]. The antipodal Vivaldi antenna (AVA) offers many advantages such as good return loss, minimal signal distortion, and does not influence the UWB band pulse shape. The basic shape of Vivaldi antenna consists of a feed line, which is usually microstrip or stripline, and the radiating structure. Many designs of Vivaldi antenna have been reported with difference radiating structure. The exponentially tapered curves are the most solution that can provide broad band [4]. One major requirement is miniaturization of UWB antenna due to devices are becoming more and more compact and portable

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in many applications. The demand of miniaturized antenna is ever increasing as the inception of radio-frequency devices [5]. The main point of electrically small antenna (ESA) is: antenna dimension is much smaller than the operating wavelength. Currently for fabrication of miniaturized antennas mostly use high dielectric and low loss materials as substrates. Practically it is possible to realize substrate with approximately $\varepsilon_r = 12$ dielectric constant. On the over hand, the using of magnetodielectric materials (MDMs) are also miniaturize antenna size, but by the higher factor than high permittivity dielectric material, however using moderate values of $\varepsilon_r$ and $\mu_r$. MDM ferrites possess relatively high permeability and permittivity simultaneously over a wide frequency range, which are effective in reducing the electromagnetic wavelength [6–8]:

$$\lambda = \frac{\lambda_0}{\sqrt{\mu_r \varepsilon_r}}. \tag{1}$$

**Problem Statement.** In this paper MDM based AVA is investigated and the miniaturization in the geometrical surface, about four times in comparison with AVA without substrate is demonstrated. The structure of antipodal Vivaldi antenna is shown in Fig. 1. The proposed antenna includes two main parts: feed line and the radiation

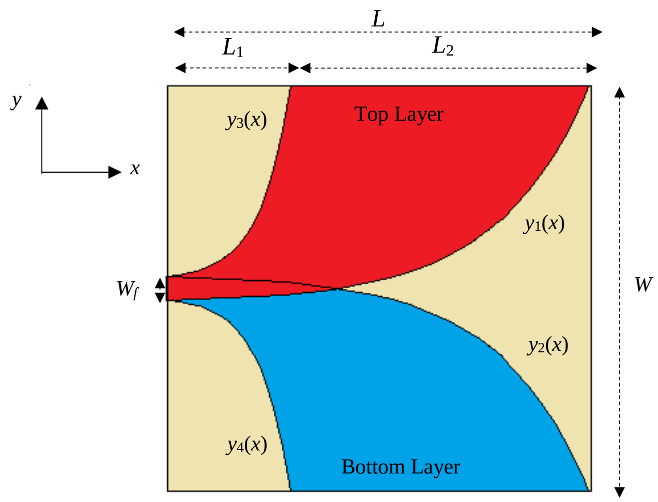


Fig. 1. The structure of designed AVA.

flares. The shape of the flares is designed in the form of elliptical curves. The elliptical configuration presents especially good broadband characteristics due to the smooth transition between the radiation flares and the feeding line. Equation for tapered slot is given by [4, 9]:

$$y = \pm (C_1 e^x + C_2), \tag{2}$$

where $C_1$ and $C_2$ are given by:

$$C_1 = \frac{y_2 - y_1}{e^{ax_2} - e^{ax_1}}, \tag{3}$$

$$C_2 = \frac{y_1 e^{ax_2} - y_2 e^{ax_1}}{e^{ax_2} - e^{ax_1}}. \tag{4}$$

In these equations $C_1$ and $C_2$ are constants, $a$ is a rate of increase of exponential curve; $x_1$, $y_1$, $x_2$ and $y_2$ accordingly are start and end points of exponential curve [1]. In the design the start and end points of exponential curves are:

$$\begin{cases} y_1(x) \to x_1 = 0, \quad x_2 = L, \quad y_1 = -\frac{W_f}{2}, \quad y_2 = \frac{W}{2}, \\ y_2(x) \to x_1 = 0, \quad x_2 = L, \quad y_1 = \frac{W_f}{2}, \quad y_2 = -\frac{W}{2}, \\ y_3(x) \to x_1 = 0, \quad x_2 = L_1, \quad y_1 = \frac{W_f}{2}, \quad y_2 = \frac{W}{2}, \\ y_4(x) \to x_1 = 0, \quad x_2 = L_1, \quad y_1 = -\frac{W_f}{2}, \quad y_2 = \frac{W}{2}. \end{cases} \tag{5}$$

Theoretically, the upper frequency limit of a Vivaldi antenna is infinity. The lower frequency limit depends mainly on the width of antenna and the effective dielectric constant. Given the lowest frequency of operation range $(f_{\min})$, thickness of the substrate $(h)$, its dielectric $(\varepsilon_r)$ and magnetic $(\mu_r)$ constant the width $(W)$ and length $(L)$ of the antenna structure is calculated using the following equation [2]:

$$W = L = \frac{c}{2 f_{\min} \sqrt{\mu_{eff} \varepsilon_{eff}}}. \tag{6}$$

**Research Results.** AVA on a free space, high constant dielectric and magnetodielectric ferrite substrates at $f_{\min} = 1\ GHz$ minimum operating frequency is researched and designed. For comparing with used high dielectric AVA parameters, the characteristics of the MDM material are chosen, thus $\mu_r \varepsilon_r$ is equal to the permittivity of the selected high dielectric material: $\mu_r \varepsilon_r = 1 \cdot \varepsilon_{r_1}$. For increasing miniaturization coefficient the Magnetodielectric ferrite material is used with high dielectric and magnetic constant.

Full-wave numerical analysis based on the FEM/MoM is conducted to investigate AVA based on dielectric and MDM in order to minimize antenna sizes. Antennas are designed in FEKO environment.

***AVA Design Without Substrate.*** At the first stage the AVA without substrate: $\varepsilon_r = \mu_r = 1$ is considered, distance between top and bottom layers: $h = 1\ mm$. Based on Eq. 6, the structural parameters of AVA: $W = L = 24\ cm$, $W_f = 8.5\ mm$, as line with 50 Ω impedance are estimated.

The coefficients of Eq. (2) are obtained during the simulation by optimizing reflection and radiation characteristics. As a result, the end point of $y_3(x)$ and $y_4(x)$ curved is $L_1 = 8\ cm$, the equations for top and bottom tapered slots are:

$$\begin{cases} y_1(x) = 62.5 \cdot 10^{-5} e^{41x} - 62.5 \cdot 10^{-5}, \\ y_2(x) = -(62.5 \cdot 10^{-5} e^{41x} - 62.5 \cdot 10^{-5}), \\ y_3(x) = 100 \cdot 10^{-5} e^{100x} - 100 \cdot 10^{-5}, \\ y_4(x) = -(100 \cdot 10^{-5} e^{100x} - 100 \cdot 10^{-5}). \end{cases} \tag{7}$$

As shown in the Fig. 2, antenna voltage standing wave ratio (VSWR) $< 2.5$ at the $f = 1 \ldots 23.8$ *GHz* frequency range. At $1 \ldots 23.8$ *GHz* frequency range antenna gain in the main radiation direction changes from $4 \ldots 13.2$ *dBi* (see Fig. 3), beamwidth in $\theta$ plane is $2\theta_{0.5} = 24.8^\circ \ldots 164.2^\circ$, in $\varphi$ plane: $2\varphi_{0.5} = 40^\circ \ldots 76^\circ$ (see Fig. 4). Antenna side lobe level (SLL) is: SLL$= 1.4 \ldots 10$ *dB*.

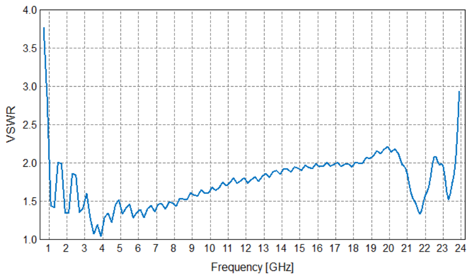


Fig. 2. VSWR vs frequency AVA on a free space.

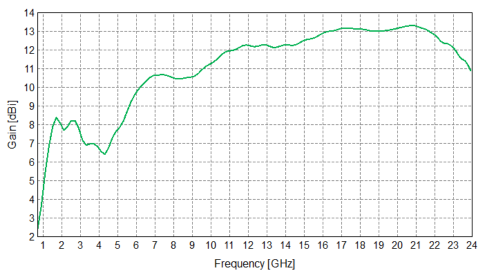


Fig. 3. Gain variation vs frequency of AVA on a free space.

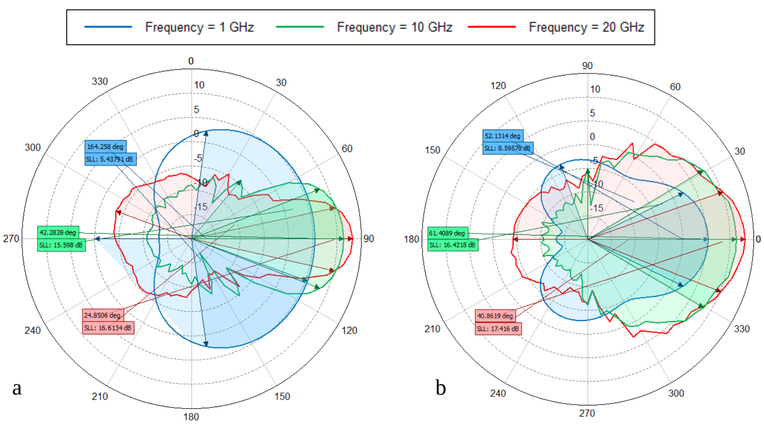


Fig. 4. AVA radiation pattern at 1, 10 and 20 *GHz* frequency in $\theta$ (a) and $\varphi$ (b) plane.

In order to further understand the behavior of the AVA structure, the current distribution of the free space-based AVA is investigated, which is shown in Fig. 5. As shown in Figure, at whole working frequency range antenna approximately have the same current distribution.

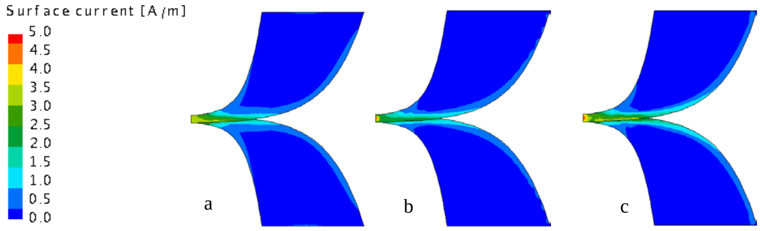


Fig. 5. Surface Current Distribution on AVA without substrate at 1 (a), 10 (b), 20 *GHz* (c) frequencies.

***AVA Characteristics Based on High Dielectric Constant.*** Farther, AVA based on with low loss and high dielectric constant substrate $(\text{tg}\,\delta = 0.005, \varepsilon_r = 11.7)$ is studied and designed. The thickness of substrate is chosen as $h = 1$ *mm*. Minimum operating frequency is $f_{\min} = 1$ *GHz*. Using Eq. 5, it's calculated structural parameters of AVA: $W = L = 155$ *mm*, $W_f = 2$ *mm*, as line with 50 Ω impedance.

The coefficients of Eq. (2) and end points of $y_3(x)$ and $y_4(x)$ are obtained during the simulation optimizing reflection and radiation characteristics. As a result, the end point of $y_3(x)$ and $y_4(x)$ curved is $L_1 = 77.6$ *mm*, and obtained equations for top and bottom tapered slots are:

$$\begin{cases} y_1(x) = 50 \cdot 10^{-5} e^{33x} - 50 \cdot 10^{-5}, \\ y_2(x) = -(50 \cdot 10^{-5} e^{33x} - 50 \cdot 10^{-5}), \\ y_3(x) = 50 \cdot 10^{-5} e^{70x} - 50 \cdot 10^{-5}, \\ y_4(x) = -(50 \cdot 10^{-5} e^{70x} - 50 \cdot 10^{-5}). \end{cases} \quad (8)$$

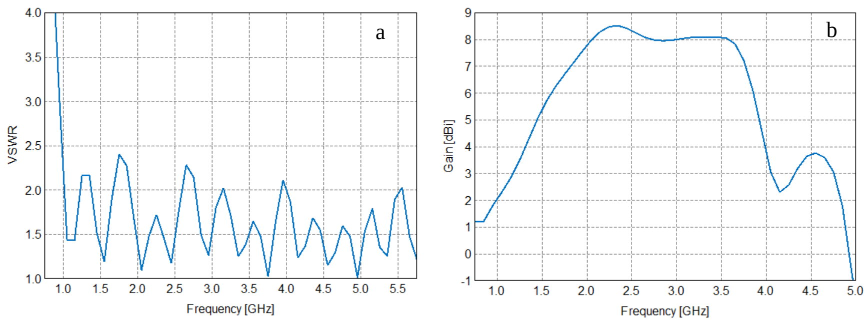


Fig. 6. AVA VSWR (a) and gain (b) vs. frequency.

As shown in the Fig. 6, antenna VSWR $< 2.5$ at the $f \geq 1$ *GHz* frequency range. At $1 \ldots 4.8$ *GHz* frequency range antenna gain in the main radiation direction is $2 \ldots 8.5$ *dBi* (see Fig. 6), beamwidth in $\theta$ plane is $2\theta_{0.5} = 30^\circ \ldots 179^\circ$, $\varphi$ in plane: $2\varphi_{0.5} = 34.5^\circ \ldots 194^\circ$ (see Fig. 7). Antenna side lobe level is: SLL=2.8...11.9 *dB*.

Fig. 8 shows surface current distribution at 1, 2 and 4 *GHz* frequencies.

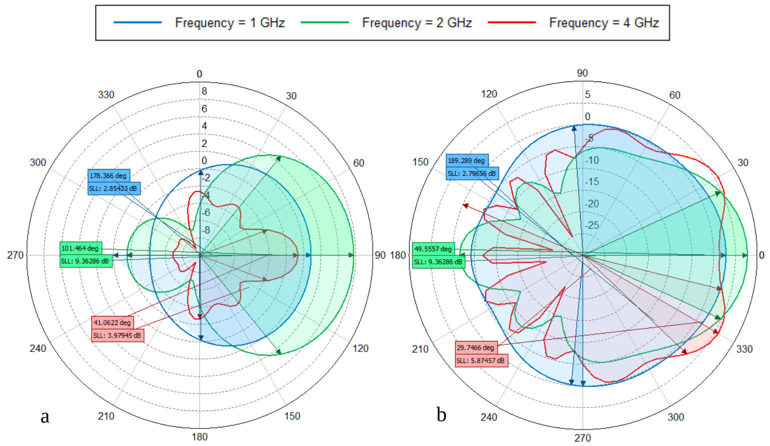


Fig. 7. High dielectric constant material based AVA radiation pattern in $\theta$ and $\varphi$ plan at different frequencies.

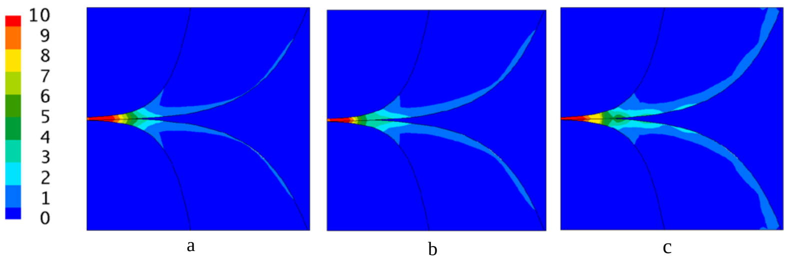


Fig. 8. AVA surface current distribution at 1 (a), 2 (b), 4 $GHz$ (c) frequencies.

As shown in Figure, at whole working frequency range antenna approximately have the same current distribution.

***AVA Characteristics Based on MDM.*** For comparing with used high dielectric AVA parameters the characteristics of the MDM material are chosen, thus $\mu_r\varepsilon_r$ is equal to the permittivity of the selected high dielectric material: $\mu_r\varepsilon_r = 1 \cdot \varepsilon_r 1$. Thus, antenna is designed on a magnetodielectric ferrite substrate with dielectric constant $\varepsilon_r = \mu_r = 3.42$, thickness $h = 1\ mm$, dielectric loss tangent $\mathrm{tg}\,\delta < 0.01$ and magnetic loss tangent $\mathrm{tg}\,\delta = 0.01$. Minimum operating frequency is $f_{\min} = 1\ GHz$. Using Eq. 5, it's calculated structural parameters of AVA: $W = L = 155\ mm$; $W_f = 3.5\ mm$, as line with 50 $\Omega$ impedance.

The coefficients of these equations are obtained during the simulation optimizing reflection and radiation characteristics. As a result, the end point of $y_3(x)$ and $y_4(x)$ curved is $L_1 = 67\ mm$, and obtained equations for top and bottom tapered slots are:

$$\begin{cases} y_1(x) = 70 \cdot 10^{-5} e^{41x} - 70 \cdot 10^{-5}, \\ y_2(x) = -(70 \cdot 10^{-5} e^{41x} - 70 \cdot 10^{-5}), \\ y_3(x) = 0.5 \cdot 10^{-3} e^{100x} - 0.5 \cdot 10^{-3}, \\ y_4(x) = -(0.5 \cdot 10^{-3} e^{100x} - 0.5 \cdot 10^{-3}). \end{cases} \tag{9}$$

Full-wave numerical analysis based on the FEM/MoM was conducted to investigate AVA based on magnetodielectric material in order to minimize antenna sizes. As shown in the Fig. 9, antenna VSWR$< 2.5$ at the $f \geq 1$ $GHz$ frequency range. At $1\ldots5.25$ $GHz$ frequency range antenna gain in the main radiation direction is $2\ldots8.5$ $dBi$ (see Fig. 9), beamwidth in $\theta$ plane is $2\theta_{0.5} = 37^\circ\ldots179^\circ$, in $\varphi$ plane: $2\varphi_{0.5} = 34.5^\circ\ldots194^\circ$ (see Fig. 10). Antenna side lobe level is: $SLL = 2.5\ldots10.5$ $dB$.

Fig. 11 shows surface current distribution at 1, 2.5 and 5 $GHz$ frequencies. As shown in Figure, at whole working frequency range antenna approximately have the same current distribution. For comparing with high constant dielectric-based antenna, in MDM based antennas, strong field confinement reduces, and the medium becomes far less capacitive.

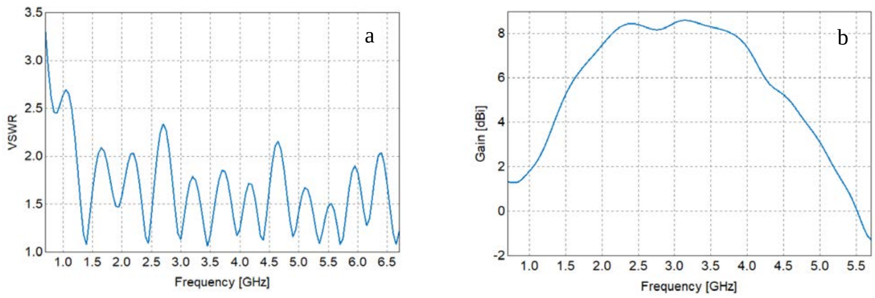


Fig. 9. MDM based AVA VSWR and gain.

***AVA Miniaturization by High Factor.*** For increasing miniaturization factor the magnetodielectric ferrite material is used with high dielectric and magnetic constant: $\varepsilon_r = \mu_r = 8$, thickness $h = 1$ $mm$, dielectric loss tangent $\operatorname{tg}\delta < 0.01$ and magnetic loss tangent $\operatorname{tg}\delta = 0.01$. Minimum operating frequency is $f_{\min} = 1$ $GHz$. Using Eq. 5, it's calculated structural parameters of AVA: $W = L = 12$ $cm$; $W_f = 3.5$ $mm$, as line with 50 $\Omega$ impedance.

As a result, the end point of $y_3(x)$ and $y_4(x)$ curved is $L_1 = 40$ $mm$, and obtained equations for top and bottom tapered slots are:

$$\begin{cases} y_1(x) = 40 \cdot 10^{-5} e^{42x} - 40 \cdot 10^{-5}, \\ y_2(x) = -(40 \cdot 10^{-5} e^{42x} - 40 \cdot 10^{-5}), \\ y_3(x) = 40 \cdot 10^{-5} e^{120x} - 40 \cdot 10^{-5}, \\ y_4(x) = -(40 \cdot 10^{-5} e^{120x} - 40 \cdot 10^{-5}). \end{cases} \tag{10}$$

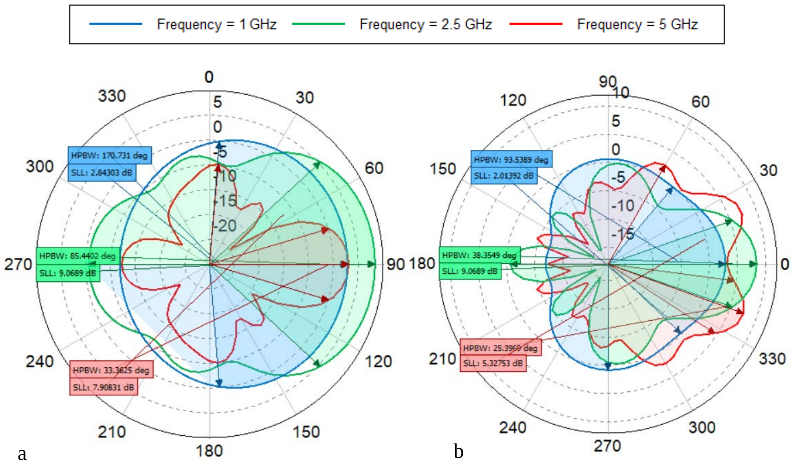


Fig. 10. MDM based antenna radiation pattern in $\theta$ and $\varphi$ plan at different (1; 2.5 and 5 $GHz$) frequencies.

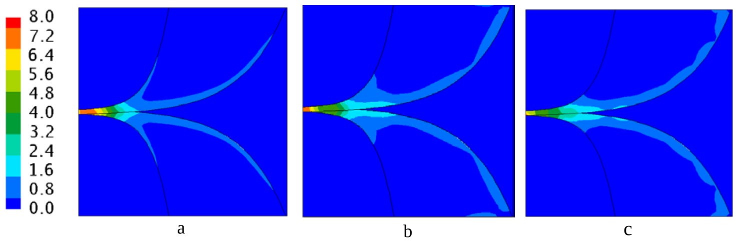


Fig. 11. MDM based AVA surface current distribution at (a) 1, (b) 2.5, (c) 5 $GHz$ frequencies.

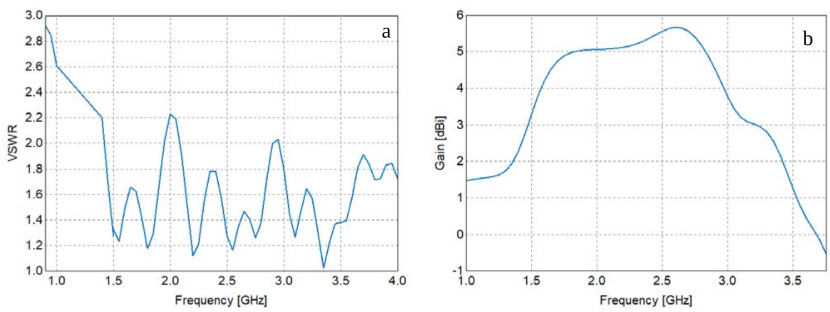


Fig. 12. AVA VSWR and gain.

As shown in the Fig. 12, antenna VSWR$<2.7$ at the $f \geq 1$ $GHz$ frequency range. At $1\ldots3.5$ $GHz$ frequency range antenna gain in the main radiation direction is $1.5\ldots5.7$ $dBi$ (see Fig. 12), beamwidth in $\theta$ plane at $1\ldots3.5$ $GHz$ frequency range is $2\theta_{0.5} = 78.3^\circ\ldots137.9^\circ$, in $\varphi$ plane: $2\varphi_{0.5} = 44^\circ\ldots77^\circ$ (see Fig. 13). Antenna side

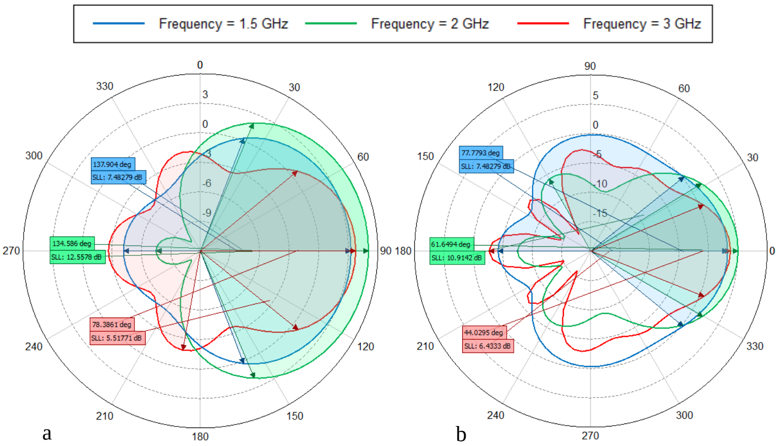


Fig. 13. Antenna radiation pattern at 1.5, 2, and 3 $GHz$ frequency in $\theta$ (a) and $\varphi$ (b) plane.

lobe level is: $SLL = 1.4 \ldots 10\ dB$.

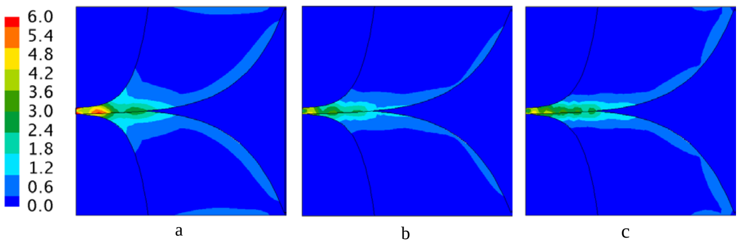


Fig. 14. MDM based AVA surface current distribution at 1.5 (a), 2 (b), 3 $GHz$ (c) frequencies.

Fig. 14 shows surface current distribution at 1.5, 2 and 5 $GHz$ frequencies. As shown in Figure, at whole working frequency range antenna approximately have the same current distribution.

**Conclusion.**

1. Based on the numerical calculations we have compared conventional miniaturization method based on high dielectric permittivity substrate with a new one based on the use of MDM as a substrate material for AVA. MDM also miniaturizes antenna size by the same factor as high permittivity dielectric material, however, using values of $\varepsilon_r = 3.2$ and $\mu_r = 3.2$ and comparing with air-based Vivaldi antenna, antenna surface minimizes 2.4 times. The using of MDM brings to the miniaturization of antenna, improvement in gain bandwidth and perfect impedance matching between material and free space over a wide bandwidth.

2. For increasing miniaturization factor the Magnetodielectric ferrite material is used with high dielectric and magnetic constant. The parameters of MDM are $\varepsilon_r = \mu_r = 8$, dielectric loss tangent $\operatorname{tg}\delta = 0.005$ and magnetic loss tangent $\operatorname{tg}\delta = 0.01$. At $f_{\min} = 1\ GHz$ minimal frequency antenna size is $120 \times 120\ (mm)$. To comparing

with the size of AVA without substrate, antenna surface minimizes 4 times. Designed antenna bandwidth is 2.5 $GHz$, where gain range is $1.5 \ldots 5.7$ $dBi$.

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## ՄԱԳՆԻՍԱԴԻԷԼԵԿՏՐԻԿՆԵՐԻ ՀԻՄԱՆ ՎՐԱ ԱՆՏԻՊՈԴԱԼ ՎԻՎԱԼԴԻ ԱՆՏԵՆԱՅԻ ՉԱՓԱՓՈՔՐԱՑՈՒՄ

Ուսումնասիրվել է բարձր դիէլեկտրական թափանցելիությամբ և մագնիսադիէլեկտրիկական ֆերիտների հիման վրա անտիպոդալ Վիվալդի անտենայի չափափոքրացումը: Համեմատվել են բարձր թափանցելիությամբ դիէլեկտրիկի և մագնիսադիէլեկտրիկների (ՄԴՄ) վրա հիմնված անտիպոդալ Վիվալդի անտենայի հիմնական բնութագրերը: Անտենայի չափն ավելի բարձր գործակցով փոքրացնելու համար օգտագործվում է ՄԴՄ ֆերիտ, որի բնութագրերը՝ $\varepsilon_r = \mu_r = 8$: Վերլուծությունը ցույց է տալիս, որ ՄԴՄ-ի վրա հիմնված անտենայի մակերեսը նվազեցվում է 4 անգամ՝ համեմատած առանց փակդիրի Վիվալդի անտենայի հետ: Անտիպոդալ Վիվալդի անտենայի չափերն են $120\times120\times1$ (*մմ*):

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## МИНИАТЮРИЗИРОВАННАЯ АНТИПОДНАЯ АНТЕННА ВИВАЛЬДИ НА ОСНОВЕ МАГНИТОДИЭЛЕКТРИЧЕСКИХ МАТЕРИАЛОВ

Исследована миниатюризация антиподной антенны Вивальди (ААВ) на основе материалов с высокой диэлектрической проницаемостью и магнитодиэлектрических ферритов. Сравнены основные параметры ААВ на основе высокодиэлектрических и магнитодиэлектрических материалов (МДМ). Для еще более уменьшения размера антенны был применен феррит МДМ с параметрами $\varepsilon_r = \mu_r = 8$. Проведенные анализы показали, что поверхность ААВ на основе МДМ уменьшается в 4 раза по сравнению с антенной Вивальди воздушного базирования. Размеры разработанной ААВ $120\times120\times1$ (*мм*).