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REDUCING INFLUENCE OF HARDWARE OF COMMUNICATION STATION ON CHARACTERISTICS OF ASYMMETRIC BICONICAL DIPOLE USING MAGNETO-DIELECTRIC SUBSTRATE ON FINITE-SIZE METAL SCREEN

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Based on the approximate analytical solution previously obtained by the authors to the problem of excitation (radiation, scattering) of electromagnetic waves by an asymmetric biconical dipole with distributed surface impedance (constant and variable) in a free space, the recommendations are proposed for reducing the influence of the hardware of a communication station on the characteristics of the such dipole using a magneto-dielectric substrate on a finite-size metal screen. Comparison of numerical and experimental results for a dipole in free space confirms the adequacy of the proposed mathematical model to the real physical process. Numerical results are given for the input characteristics and radiation fields of the dipole with magneto-dielectric substrate in the case of its asymmetric feeding by a point source.
Keywords: *Biconical dipole; Distributed surface impedance; Magneto-dielectric substrate; Finite-size metal screen; Asymmetric excitation; Current distribution; Input characteristics*
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INTRODUCTION

Among modern communication systems (both mobile and stationary), the leading place is occupied by multi-frequency (multi-channel) structures. The main functional element of such devices are antennas, which differ from each other in their design features, for example, they can be single-element structures (mono-frequency) or multi-element (multi-frequency) structures [1]. At the same time, the operation of a multi-frequency antenna, implemented by expanding the operating band (broadband antenna), in turn, can lead to a significant weakening of its noise-immune interference immunity properties. Typically, designers take the path of combining several antennas operating at different frequencies into one structure [2-8]. This approach significantly complicates the design of the antenna device and this is a difficult factor to overcome on the path to its miniaturization. Note, that since in the abovementioned publications and other similar ones, the antennas are located outside the phone body, so the influence of the phone's internals on their characteristics is significantly minimized.

In recent decades, a large number of publications have appeared devoted to multi-band printed antennas directly integrated into communication devices, for example [9-21] and references therein. In this case, the electrodynamic characteristics of the antennas are obtained using commercial programs such as ANSYS HFSS, CST Microwave Studio, FEKO and others. Calculating and optimizing the antenna characteristics using this approach requires enumeration of a large number of options, and, hence, huge amount of computer time and resources. However, it is not always clear from the text of the publications: 1) how the influence of the phone hardware on the antenna characteristics is minimized? 2) how the experimental studies were carried out, namely, together with the filling or only the case with the antenna?
The use of dipoles with an asymmetric excitation, i.e. with an arbitrary position feeding point along their length, for creating multi-band antennas has been repeatedly proposed by researchers in various publications [5], [7], [22-29]. However, in these literary sources only perfectly conducting dipoles were considered. Another solution makes use of a dipole antenna with an asymmetric excitation and distributed surface impedance, directly integrated into the body of the communication device [25-28]. In this case, the frequency response of the antenna may have several resonances that prevent the radiation (receiving) of electromagnetic waves outside the resonant frequency bands.

On the other hand, one of the additional parameters for obtaining the special characteristics of antennas in the form of a cylindrical dipole can be a change of the radius of the cross section of the dipole along its length. In the case of a linear increase in the radius of the vibrator from the feeding point of the antenna to its ends (biconical dipole), this antenna resonates at a smaller geometric length, and is also more broadband compared to a dipole of constant radius (see, for example, [27], [28], [30–41] and references in them). However, all of them are devoted to calculating the electrodynamic characteristics of perfectly conducting dipoles excited at the geometric center by a concentrated electromotive force (EMF). Also, as is known, to analyze receiving antennas it is necessary to know the current in the scattering dipole excited by the incident electromagnetic wave [38]. It is worth to notice that in [41] for operation in the three-frequency range it is offered to use three antennas in the form of symmetrical patch biconical dipoles. Moreover, it is proposed to make both the antennas themselves and the rather complex supply system from pure gold.

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The purpose of this paper is to study a multiband antenna for communication systems based on an asymmetric biconical dipole with a distributed surface impedance and arbitrary excitation, in particular, by feeding the antenna with a voltage source at a point arbitrary along the length of the dipole to create a multi-frequency operating mode. Thus, we will combine in one design all the advantages of asymmetric excitation, biconical geometry and the presence of a distributed surface impedance. Based on the approximate analytical solution previously obtained by the authors to the problem of excitation of electromagnetic waves by an asymmetric biconical dipole with distributed surface impedance (constant and variable) in a free space, the recommendations are proposed for reducing the influence of the hardware of a communication station on the characteristics of the such dipole using a magneto-dielectric substrate on a finite-size metal screen.

CHARACTERISTICS OF THE ASYMMETRIC BICONICAL DIPOLE IN A FREE SPACE

Let us limit ourselves by the linear law of the radius change $r(s)$ along the dipole with the $2L$ length and located in free space. It has the distributed internal linear impedance z_i and is excited by the electrical field $E_{0s}(s)$ of the given sources (tangential component). We assume that the dipole stays electrically thin in the operating frequency band, i.e. $kr(s) << 1$, $r(s) << 2L$, where $k = 2\pi/\lambda$, λ is the wavelength in free space. Then the integral equation relatively to the $J(s)$ current for the impedance boundary condition on the dipole surface can be written as [38]:

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}s^2} + k^2\right)\int_{-L}^{L} J(s')\frac{e^{-ik\tilde{R}(s,s')}}{\tilde{R}(s,s')}\mathrm{d}s' = -\frac{i\omega}{\cos\psi}\left[E_{0s}(s) - z_i J(s)\right], \tag{1}$$

where $\tilde{R}(s,s') = \sqrt{(s-s')^2 + r^2(s)}$, $\psi = (\psi_1 + \psi_2)/2$ ($\frac{\psi}{2\pi}$<<1), s and s' are the local coordinates related to the dipole axis and surface (Fig. 1).

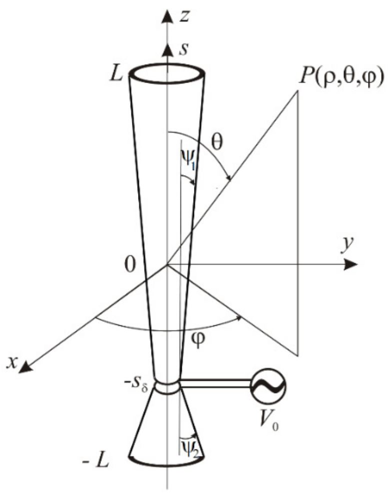


Figure 1. The geometry of structure and notations

An approximate analytical solutions of equation (1) was obtained in [27] (z_i is the constant along the dipole length) and in [28] (z_i is the variable along the dipole length) for an arbitrary field of external sources $E_{0s}(s)$ and the case of dipole feeding by the voltage generator with amplitude V_0 in the point $s = -s_\delta$ was investigated. As a result of solving equation (1), the following expressions were obtained: for the input impedance $Z_{in} = R_{in} + iX_{in}$, module of reflection coefficient in the antenna feeder with the wave impedance W $|S_{11}| = |(Z_{in} - \mathrm{W})|/|(Z_{in} + \mathrm{W})|$, the voltage standing wave ratio $\mathrm{VSWR} = (1+|S_{11}|)/(1-|S_{11}|)$ and radiation fields of the dipole.

As it is well known [25], the condition for resonance of any antenna structure is the equality on average over the period of harmonic oscillations of the near-range reactive fields of electric and magnetic types. The fulfillment of this condition mainly depends on the geometric dimensions of the antenna. In our case, we define it as the minimum value of the modulus of the reflection coefficient in the feeder line (hereinafter W =50 Ohm). The dependences of the $|S_{11}|$ versus frequency for different positions of the feeding point s_δ are presented in Fig. 2 (hereinafter z_i=0).

As can be seen, when moving s_δ from the geometric center of the dipole, there are several resonant frequencies at $2L$ =132 mm, r_δ =0.5 mm, r_L =3 mm (r_δ and r_L are the radii of the dipole in point $s = -s_\delta$ and in its end). This choice of the dipole length is due to the condition of the first resonance at the frequency f =0.850 GHz (GSM 850). One can notice that for a regular dipole with a radius r=2 mm, its length would be equal to $2L$ =156 mm.

The spatial distribution of the dipole radiation field in a free space in comparison with experimental data presented in Fig. 3. Due to the complexity of the antenna structures considered below, we will use software FEKO.

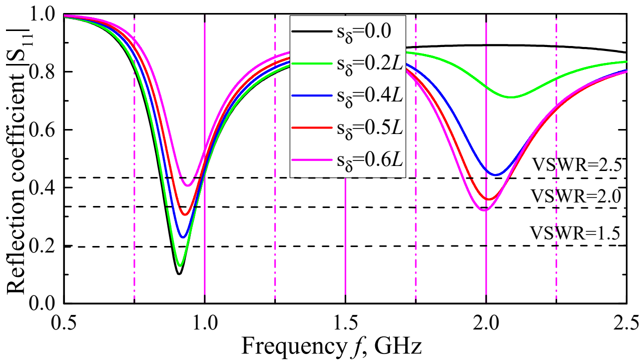


Figure 2. The dependences of the $|S_{11}|$ versus frequency for dipole in a free space for different positions of the feeding point s_δ at $2L$ =132 mm, r_δ=0.5 mm, r_L =3 mm

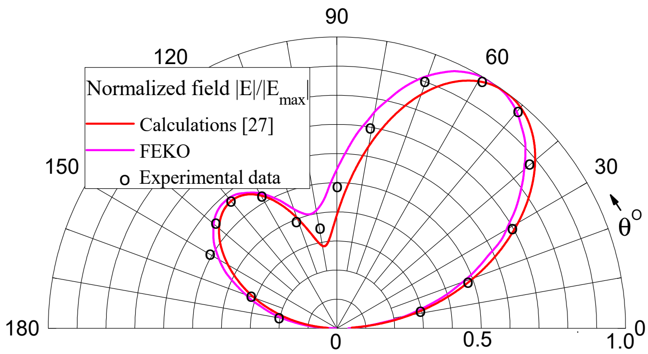


Figure 3. The spatial distribution of the dipole radiation field in a free space at $f = 0.85\text{GHz}$, $s_\delta = 0.2L$, $2L$ =138 mm, r_δ=1 mm, r_L =3 mm

INFLUENCE OF SUBSTRATE PARAMETERS ON DIPOLE CHARACTERISTICS

1. Dipole above metal screen of finite dimensions and on dielectric substrate

Fig. 4 shows the results of calculations for the cases of a dipole in free space, a dipole above a metal screen (herein after screen length L_{scr} = 140 mm, width W_{scr} = 6 mm) and on a dielectric substrate made of a material FR4 ($\varepsilon = \varepsilon' - i\varepsilon'' = 4.4 - i0.115$) with thickness d =2 mm. As it can be seen, the presence of a metal screen of finite dimensions, as well as a purely dielectric substrate, significantly worsens the resonant characteristics of the dipole.

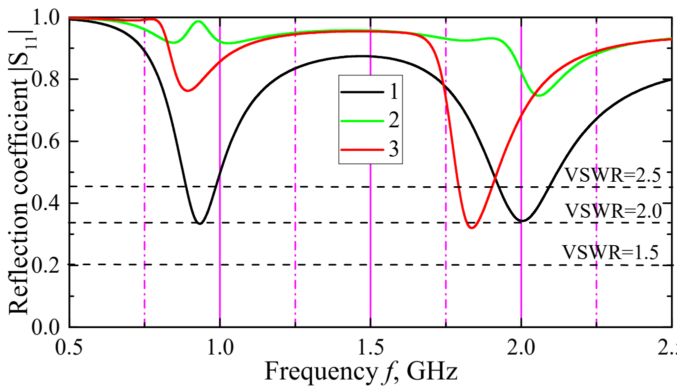


Figure 4. The dependences of the $|S_{11}|$ versus frequency at $s_\delta = 0.55L$, $2L$ =132 mm, r_δ=0.5 mm, r_L =3 mm: 1-dipole in a free space, 2- dipole above a metal screen, 3- dipole on a dielectric substrate (d =2 mm) on a metal screen.

2. Dipole with variable feeding point on dielectric substrate on screen

Fig. 5 Shows the dependences of the $|S_{11}|$ versus frequency for dipole on a dielectric substrate on a screen. As follows from the graphs, changing the position of the feeding point in this case has small effect on the resonant characteristics of the dipole.

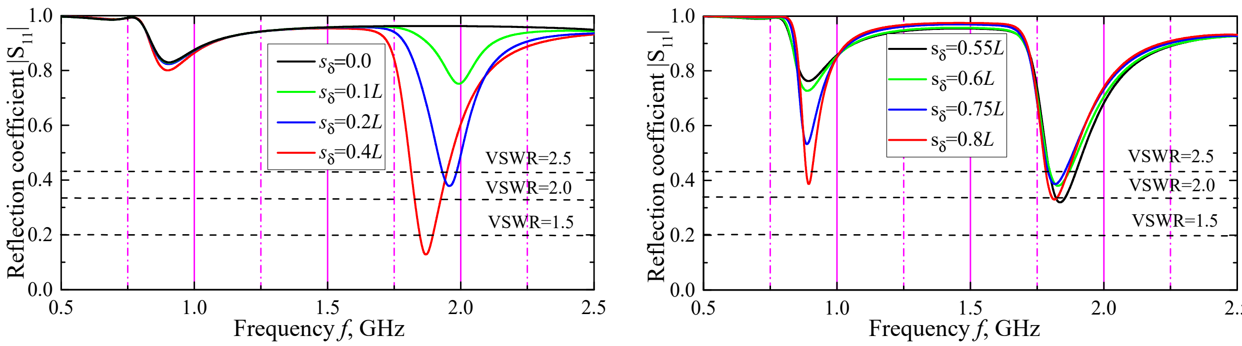


Figure 5. The dependences of the $|S_{11}|$ versus frequency for dipole on a dielectric substrate (d =2 mm) on a screen for the different positions of the feeding point s_δ at $2L$ =132 mm, r_δ=0.5 mm, r_L =3 mm

3. Dipole on magneto-dielectric substrate on screen with variable feeding point

As follows from general physical principles (mainly based on impedance concept [42]), to improve the characteristics of the dipole it is necessary to use the magnetic material as a substrate. Let us use the magneto-dielectric TDK-IR-A095 with the following electrophysical parameters in the frequency range $f = 0.5 \div 10.0$ GHz are $\varepsilon = 6.2 - i0.32$, $\mu = 0.60 - i0.32$ [43].

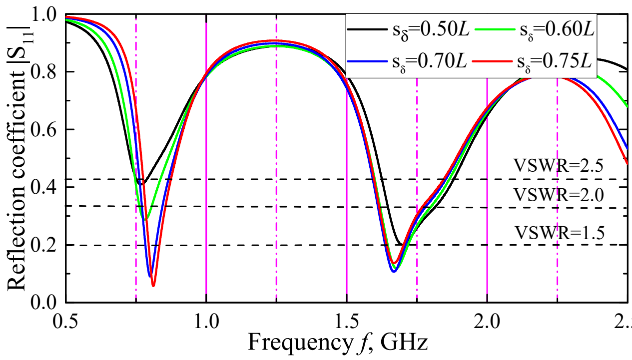


Figure 6. The dependences of the $|S_{11}|$ versus frequency for dipole on a magneto-dielectric substrate on a screen (TDK with thickness d_1 =1 mm on a screen and FR4 with thickness d_2 =1 mm under the dipole) for different positions of the feeding point s_δ at $2L$ =132 mm, r_δ=0.5 mm, r_L =3 mm.

As can be seen from the presented curves in Fig. 6, it is possible to achieve a significant decrease in the value of the reflection coefficient by changing the position of the feeding point in the given frequency range. However, the values of the resonant frequencies differ significantly from the original ones (see Fig. 2). To correct this drawback, the next step must be realized.

4. Finding the resonant length of dipole on magneto-dielectric substrate on screen

Graphs for the final resonant length $2L$ =117 mm of the dipole (in accordance with Fig. 2) are presented in Fig. 7. As can be seen, the resonant frequencies of the dipole correspond to the ranges of GSM 850 and GSM 1900.

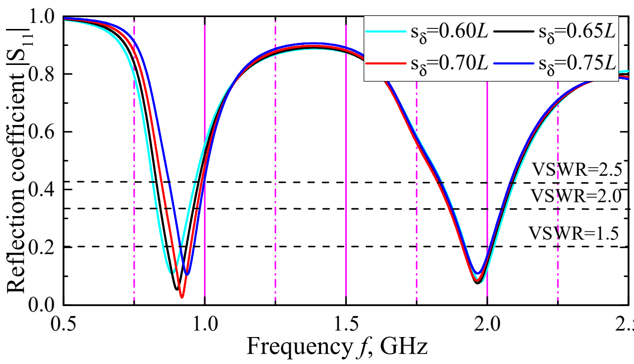
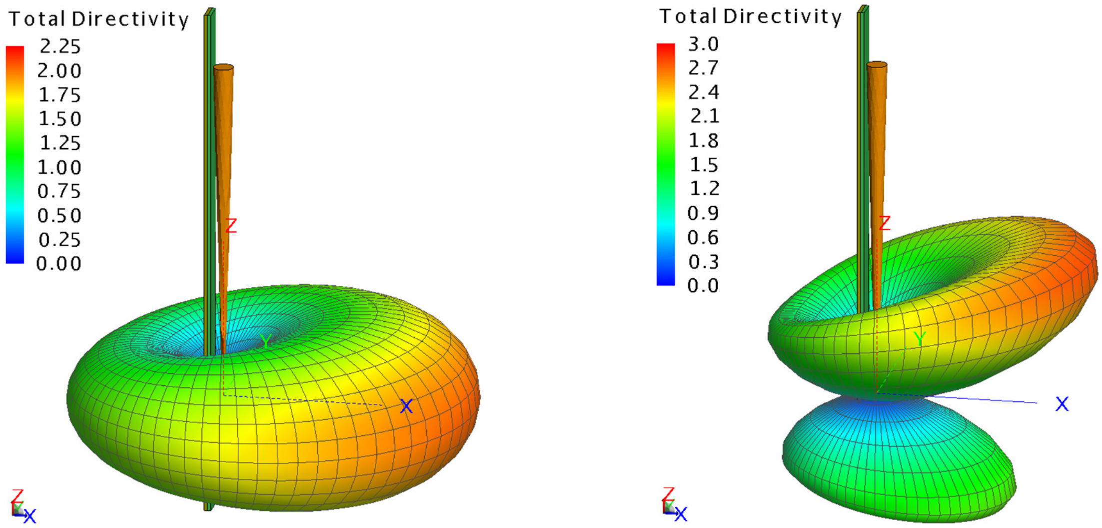


Figure 7. The dependences of the $|S_{11}|$ versus frequency for dipole on a magneto-dielectric substrate on a screen (TDK with thickness d_1 =1 mm on a screen and FR4 with thickness d_2 =1 mm under the dipole) on a screen for different positions of the feeding point s_δ at $2L$ =117 mm, r_δ=0.5 mm, r_L =3 mm (part 1).

The corresponding spatial distributions of the dipole radiation field for the resonant frequencies are represented in Fig. 8. Although the spatial distributions presented are somewhat different, this does not impair the user properties of the radiating system presented because the direction of the main maximum remains almost unchanged.



(a) $f = 0.850$ GHz (b) $f = 1.900$ GHz

Figure 8. Spatial distributions for dipole on a magneto-dielectric substrate (TDK with thickness d_1 =1 mm on a screen and FR4 with thickness d_2 =1 mm under the dipole) on a screen at $s_\delta = 0.7L$, $2L$ =117 mm, r_δ=0.5 mm, r_L =3 mm

With a further increase in the frequency range, another resonance occurs (Fig. 9). In this case, the ratio of resonant frequencies for $s_\delta = 0.7L$ is approximately 1 : 2.2 : 3.6. However, if we look at the figure more closely, we can see that this ratio is not exactly fulfilled under the influence of a change in the feeding point, so this gives reasons for an independent change in the center frequency of each of the operating frequency bands within certain limits.

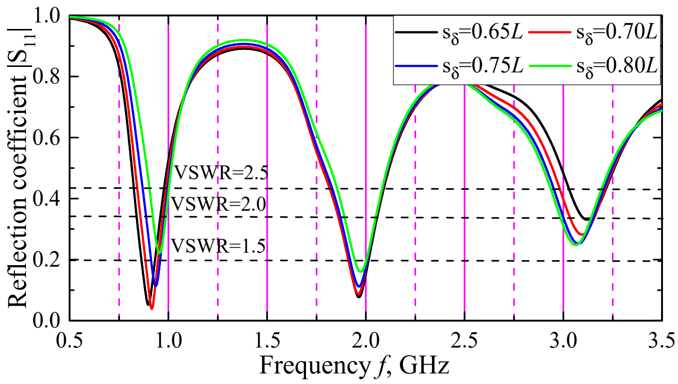


Figure 9. The dependences of the $|S_{11}|$ versus frequency for dipole on a magneto-dielectric substrate on a screen (TDK with thickness d_1 =1 mm on a screen and FR4 with thickness d_2 =1 mm under the dipole) on a screen for different positions of the feeding point s_δ at $2L$ =117 mm, r_δ=0.5 mm, r_L =3 mm (part 2).

CONCLUSION

Based on the approximate analytical solution previously obtained by the authors to the problem of excitation (radiation, scattering) of electromagnetic waves by an asymmetric biconical dipole with distributed surface impedance (constant and variable) in a free space, the recommendations are proposed for reducing the influence of the hardware of a communication station on the characteristics of the such dipole using a magneto-dielectric substrate on a finite-size metal screen. Solution correctness is confirmed by satisfactory agreement of numerical results received using the commercial software FEKO and experimental data. Numerical results are given for the input characteristics and radiation field of the dipole in the case of its asymmetric feeding by a point source. In order to reduce the interaction of the antenna with the phone hardware, the influence of the electrophysical parameters of the magneto-dielectric substrate on the characteristics of the dipole was comprehensively studied. The distinctive property of the antenna is the possibility of resonant tuning to the selected frequencies, depending on the geometric and electro-physical parameters of the dipole and substrate, which does not deteriorate the noise-immune interference immunity properties in comparison with broadband antennas. In this case, the reduction in the length of the antenna on a magneto-dielectric substrate compared to a biconical dipole in free space is 11%, and the shortening compared to a regular dipole in free space is 25%. It can be seen that the center frequencies of the channels in which the antenna operates can be independently adjusted within small limits by changing the size of the cones and the position of the feeding point. It is possible to calculate the dimensions of the dipole and the substrate parameters for other resonant frequencies. It is also planned to further study the gain and radiation efficiency of such a structure. Analysis of radiation characteristics of the proposed dipole antenna has proved the possibility of practical applications of this antenna for multiband portable radio stations, smartphones, electronic gadgets, base stations and different antenna systems, for example, multi-channel UAV communication systems.

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ЗМЕНШЕННЯ ВПЛИВУ АПАРАТНОГО ЗАБЕЗПЕЧЕННЯ СТАНЦІЇ ЗВ'ЯЗКУ НА ХАРАКТЕРИСТИКИ АСИМЕТРИЧНОГО БІКОНІЧНОГО ДИПОЛЯ З ВИКОРИСТАННЯМ МАГНІТО-ДІЕЛЕКТРИЧНОЇ ПІДКЛАДКИ НА СКІНЧЕННО-РОЗМІРНОМУ МЕТАЛЕВОМУ ЕКРАНІ

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На основі попередньо отриманого авторами наближеного аналітичного розв'язку задачі збудження (випромінювання, розсіювання) електромагнітних хвиль асиметричним біконічним диполем з розподіленим поверхневим імпедансом (постійним і змінним) у вільному просторі запропоновано рекомендації щодо зменшення впливу апаратного забезпечення станції зв'язку на характеристики такого диполя за допомогою магніто-діелектричної підкладки на металевий екран кінцевого розміру. Порівняння чисельних та експериментальних результатів для диполя у вільному просторі підтверджує адекватність запропонованої математичної моделі реальному фізичному процесу. Наведено чисельні результати для вхідних характеристик і полів випромінювання диполя з магніто-діелектричною підкладкою за умови його несиметричного живлення точковим джерелом.

Ключові слова: *біконічний диполь; розподілений поверхневий імпеданс; магніто-діелектрична підкладка; кінцевий металевий екран; асиметричне збудження; розподіл струму; вхідні характеристики*