Paper

New type of microstrip antenna with ferroelectric layer

Józef Modelski and Yevhen Yashchyshyn

Abstract — A new type of microstrip antenna is proposed using a voltage-controlled ferroelectric thin tape in the multilayered structure. This paper presents the ferroelectric thin tape, its theoretical analysis and design. The results indicate that this concept has many advantages, is very practical and promising. It gives possibilities of several applications, e.g. in smart antennas.

Keywords — microstrip antenna, multilayered structure, ferroelectric thin tape, smart antennas.

1. Introduction

Microstrip antennas have over thirty years history [1], but during the last decade, microstrip antenna technology has been the most rapidly developing research topic in the antenna field [2], because of the huge demand in markets of personal and satellite communications, wireless local networks and intelligent vehicle systems. Microstrip antennas are well known for their highly desirable physical characteristics such as low profile, light weigh, low cost, ruggedness and they are well suited to integration with MICs. In comparison to traditional antenna elements, however, the electrical performance of the basic microstrip antenna suffers from a number of serious drawbacks, e.g. narrow bandwidth, high feed network losses, poor cross polarization, and low power handling capacity. In many applications, the electrically shaping of the radiation pattern has received a great deal of attention. New possibilities are emerged by using new materials and structures. Below, a new type of multilayered microstrip antenna has been proposed, which seems to be very promising for applications in smart antennas and phase-arrays.

2. Antenna configuration

Figure 1 shows a basic configuration of the discussed microstrip antenna. The main feature of the ferroelectric antennas is the change of ferroelectric material permittivity with an applied dc (direct current) control voltage. The multilayer substrate consists of thin ferroelectric tape sandwiched between dielectric slabs (also for the heat transferring). Substrates are located on the conducting plate. Ferroelectric tape has thickness h_3 and is made up of ferroelectric material which permittivity (ε_3) can be changed by applying and varying the dc electric field. DC voltage source V is used as shown in Fig. 1. Dielectric slabs have thicknesses h_2 and h_4 and permittivities ε_2 and ε_4, respectively, and conducting plate is described by thickness h_1 and conductivity σ. Microstrip line with current J_x^e is a source which excites the multilayer structure. Characteristics of this microstrip antenna depends on parameters of dielectric substrate (i.e. thicknesses and permittivities). Radiating elements employing ferroelectric materials may give much better performance with compared to ferrite ones, because of their high power handling capability, low drive power, full military temperature range of operation and low cost [3].

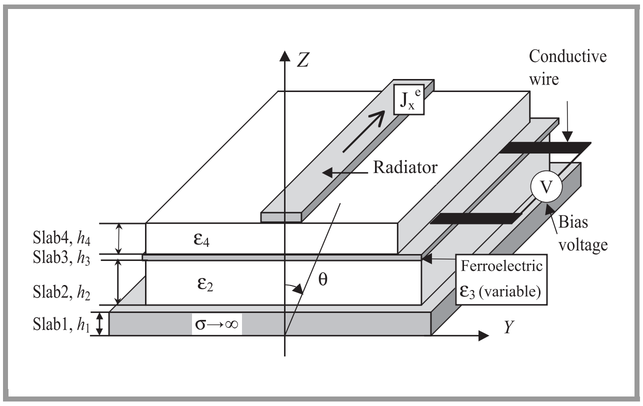

Fig. 1. Basic configuration of the ferroelectric microstrip antenna.

Ferroelectric materials of series (Ba-Sr)TiO_3 (BSTO), (Pb-Sr)TiO_3 and (Pb-Ca)TiO_3 and similar titanates (for which the Curie temperature is in the vicinity of room temperature) are well suited for microstrip applications. Ferroelectric materials for high performance microwave applications should exhibit: a large variation of the dielectric constant with applied dc biasing fields, low loss tangent over the range of operating dc bias voltages, insensitivity of dielectric properties to changes in environmental condition (e.g. ambient temperature variation), and maximum reproducibility of the dielectric properties with respect to the applied dc voltage. Materials such as (Ba-Sr)TiO_3 series exhibit a significant variation of the dielectric constant with applied dc biasing fields at microwave frequencies (e.g. from 1000 to 6000) because the Curie temperature is close to the room temperature. Also, the loss tangent value of barium-strontium titanate materials can be reduced to 0.005 by adding a small percentage (1 to 4 percent) of iron, nickel or magnesium to the material mixture. The dielectric constant variation with dc biasing field is larger if the Curie temperature for a BSTO composition is closer to the ambient temperature (25°C) [4, 5].

3. Antenna analysis

The full-wave method has been applied for theoretical analysis. Analysis of the multilayered substrate is based on the calculations of electromagnetic field excited by the source inside multilayered space (with different variable parameters as permittivity, permeability and conductivity).

Assume, that dependence on the time is $e^{-i\omega t}$ and distribution of the current density is $\vec{j}(M)$ in space V. The associated electric and magnetic fields due to this current are given by:

$$\vec{H} = rot\vec{A}; \quad \vec{E} = i\omega\left\{-\vec{A} + grad\left[\frac{\mu}{k^2} div\frac{\vec{A}}{\mu}\right]\right\}, \tag{1}$$

where

$$\vec{A}(M) = \frac{1}{4\pi}\iiint\limits_V \widehat{G}(M, M_0)\,\vec{j}(M_0)\,dv_{M_0} \tag{2}$$

is the vector potential integral and $\widehat{G}(M, M_0)$ is tensor function given by

$$\widehat{G}(M, M_0) = \\ = \left\{\begin{matrix} G_0(M,M_0) & 0 & 0 \\ 0 & G_0(M,M_0) & 0 \\ \mu(z)\frac{\partial g(M,M_0)}{\partial x} & \mu(z)\frac{\partial g(M,M_0)}{\partial y} & \frac{\mu(z)}{\widetilde{\varepsilon}(z_0)}G_1(M,M_0)\end{matrix}\right\}, \tag{3}$$

where: $k = \omega\sqrt{\widetilde{\varepsilon}\mu}$ – wave number; μ – permeability; $\widetilde{\varepsilon} = \varepsilon + i\frac{\sigma}{\omega}$ – complex permittivity.

Functions G_0, g, G_1 are solutions of the boundary problem. They depend only on coordinates z, z_0 and $\rho = \sqrt{(x-x_0)^2 + (y-y_0)^2}$ and can be written as:

$$G_0=\int_0^\infty J_0(\chi\rho)\Phi_0(\chi,z,z_0)\chi d\chi; \quad g=\int_0^\infty J_0(\chi\rho)\varphi(\chi,z,z_0)\chi d\chi;$$
$$G_1=\int_0^\infty J_0(\chi\rho)\Phi_1(\chi,z,z_0)\chi d\chi. \tag{4}$$

If we will introduce the fundamental function $U_a^\alpha(\chi, z, z_0)$, then dependence (4) can be given as

$$\Phi_0 = U_\mu^0; \quad \varphi = \frac{1}{\chi^2}\left\{U_{\widetilde{\varepsilon}}^1 - \frac{1}{\mu}\cdot\frac{dU_\mu^0}{dz}\right\}; \quad \Phi_1 = U_{\widetilde{\varepsilon}}^0. \tag{5}$$

The fundamental function for the field in half-space above radiator ($z \geq z_0$) can be accomplished in the form:

$$U_a^\alpha(z) = 2\,\frac{(1-\alpha)Z_1(z_o)Z_2(z_0) - \alpha Z_2(z_0)}{Z_2(z_o) - Z_1(z_0)}\,e^{-\zeta_0(z-z_0)}. \tag{6}$$

Because we examine antenna with nonmagnetic substrate, the functions $Z_{1/2}$ are given by:

$$Z_2(z_0) = -\frac{\mu_0}{\zeta_0}; \qquad Z_1(z_0) = Z_1^l;$$
$$Z_1^l = \frac{\mu_0}{\zeta_4}\cdot\frac{A_4 - B_4e^{-2\zeta_4h_4}}{A_4 + B_4e^{-2\zeta_4h_4}}; \quad A_4 = \mu_0 + \zeta_4 Z_1^4; \quad B_4 = \mu_0 - \zeta_4 Z_1^4$$
$$Z_1^4 = \frac{\mu_0}{\zeta_3}\cdot\frac{A_3 - B_3e^{-2\zeta_3h_3}}{A_3 + B_3e^{-2\zeta_3h_3}}; \quad A_3 = \mu_0 + \zeta_3 Z_1^3; \quad B_3 = \mu_0 - \zeta_3 Z_1^3$$
$$Z_1^3 = \frac{\mu_0}{\zeta_2}\cdot\frac{A_2 - B_2e^{-2\zeta_2h_2}}{A_2 + B_2e^{-2\zeta_2h_2}}; \quad A_2 = \mu_0 + \zeta_2 Z_1^2; \quad B_2 = \mu_0 - \zeta_2 Z_1^2$$
$$Z_1^2 = \frac{\mu_0}{\zeta_1}\cdot\frac{1 - e^{-2\zeta_1h_1}}{1 + e^{-2\zeta_1h_1}}, \tag{7}$$

where: $k_1 = \sqrt{\frac{\omega\mu_0\sigma}{2}}(1 - i)$; $\zeta_m = \sqrt{\chi^2 - k_m^2}$; $k_m = \omega\sqrt{\widetilde{\varepsilon}_m\mu_0}$ ($m = 0, 2, 3, 4$) – wave number of the mth layer.

The structure has been restricted to the 2D geometry (is not depended on coordinate "x"). In this case the electromagnetic field can be presented as:

$$E_x = i\omega\frac{J_x^e}{4\pi^2}\int_{-\infty}^{\infty}\frac{Z_1(z_0)}{Z_2(z_0) - Z_1(z_0)}\,e^{-i\chi(y-y_0) - i\zeta_0(z-z_0)}d\chi. \tag{8}$$

This equation is simply a Fourier transform. It permits to utilize the fast Fourier transform (FFT) for numerical calculation. The far field has been obtained on the base of stationary phases method. Then pattern of the ferroelectric microstrip antenna can be written as:

$$F(\theta) = -j\,\frac{Z_1(\theta)\beta_0}{Z_2(\theta) - Z_1(\theta)}, \tag{9}$$

where:

$$Z_2(\theta) = -\frac{\mu_0}{\beta_0};$$
$$Z_1(\theta) = \frac{\mu_0}{\beta_0}\cdot\frac{\mu_0(1-\vartheta_4) + \beta_0 Z_1^4(1+\vartheta_4)}{\mu_0(1+\vartheta_4) + \beta_0 Z_1^4(1-\vartheta_4)};$$
$$Z_1^4(\theta) = \frac{\mu_0}{\beta_3}\cdot\frac{\mu_0(1-\vartheta_3) + \beta_3 Z_1^3(1+\vartheta_3)}{\mu_0(1+\vartheta_3) + \beta_3 Z_1^3(1-\vartheta_3)};$$
$$Z_1^3(\theta) = \frac{\mu_0}{\beta_2}\cdot\frac{\mu_0(1-\vartheta_2) + \beta_2 Z_1^2(1+\vartheta_2)}{\mu_0(1+\vartheta_2) + \beta_2 Z_1^2(1-\vartheta_2)};$$
$$Z_1^2(\theta) = \frac{\mu_0}{\beta_1}\cdot\frac{(1-\vartheta_1) + (1+\vartheta_1)\beta_1/\beta_0}{(1+\vartheta_1) + (1-\vartheta_1)\beta_1/\beta_0},$$

where:
$\vartheta_m = e^{-2H_mB_m}$; $\beta_m = j\sqrt{k_m^2 - k_0^2\sin^2\theta}$, $m = 0, 1, 2, 3, 4$;
$k_m = \omega\sqrt{\mu_0\varepsilon_m}$, $m = 0, 2, 3, 4$.

4. Results

The characteristics of the ferroelectric microstrip antenna have been investigated. Figure 2 shows H-plane radiation pattern of this antenna for different permittivity values. As shown in the Fig. 2, the permittivity change (by varying the dc bias) gives possibility to create different radiation patterns. The following cases have been calculated: slab1 – $h_1 = 0.02\lambda$ and $\sigma \to \infty$; slab2 – $h_2 = 0.004\lambda$ and $\varepsilon_2 = 9 \cdot \varepsilon_0$; slab3 (ferroelectric) – $h_3 = 0.00002\lambda$ and ε_3 can be changed (e.g. from 900 to 9000); slab4 – $h_4 = 0.007\lambda$ and $\varepsilon_4 = 2 \cdot \varepsilon_0$, where λ – length wave. Beamwidth pattern for case 2 ($\varepsilon_3 = 3600 \cdot \varepsilon_0$) is about 33° with two zeros. For case 3 beamwidth pattern is about 52° ($\varepsilon_3 = 9000 \cdot \varepsilon_0$) without zeros (see Fig. 2, curve 2 and 3, respectively). The pattern of radiating element changes its shape and zeros localization of the beam by varying permittivity of ferroelectric tape. Figure 3 shows dependence of the zeros localization in the radiating element pattern, by varying the dc electric field of ferroelectric material (parameters of the structure have been shown above). This permits to use such radiating element into several applications, e.g. for smart antenna arrays [6]. A linear N-isotropic elements array has $N-1$ degrees of the freedom. Therefore, it is possible to own $N-1$ independent control zeros pattern. If the pattern of the radiating nonisotropic element has own two zeros, then the linear N-nonisotropic elements array has own $N+1$ control zeros (e.g., two more degrees of freedom). This permits to shape assignment pattern for smart antenna.

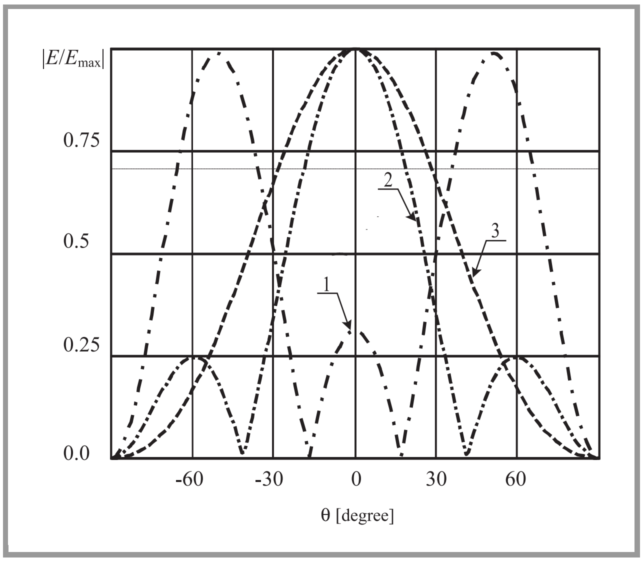

Fig. 2. H-plane radiation pattern of the ferroelectric microstrip antenna for different permittivity. Explanations: *1* – $\varepsilon_3 = 1800\varepsilon_0$; *2* – $\varepsilon_3 = 3600\varepsilon_0$; *3* – $\varepsilon_3 = 9000\varepsilon_0$.

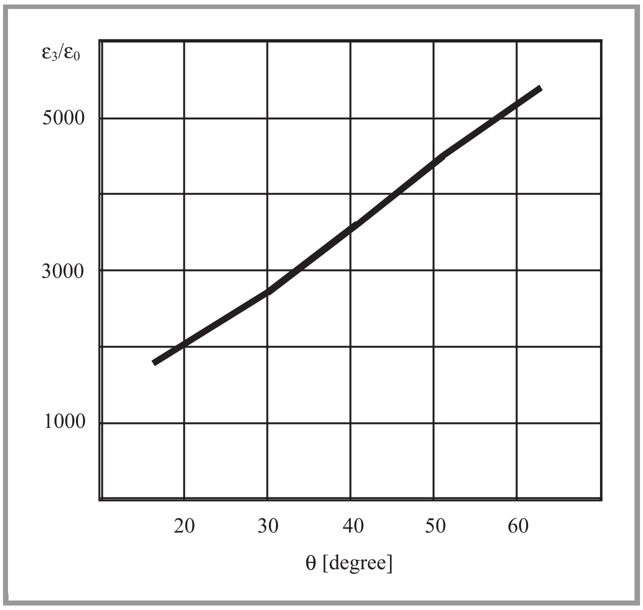

Fig. 3. Dependence of the zero localization from change permittivity of ferroelectric.

5. Conclusion

In this paper, a new type of microstrip antenna with ferroelectric layer has been presented. This novel antenna consists of multilayered structure with thin ferroelectric tape (voltage-controlled) sandwiched between two dielectric slabs, located on the conductive plate. The results of investigations indicate that proposed microstrip antenna type is perspective.

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