Tunable Periodic Deflector Structure Based on Ferroelectric Materials

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Abstract— The electrically tunable lens based on nonlinear ferroelectric materials ($Ba_{0.4}Sr_{0.6}TiO_3$) for deflecting of the microwave (MW) beam is presented. The distinctive feature of the deflector is the use of multilayer periodic structure FE/LD/FE/LD/.../FE (FE-ferroelectric, LD-linear dielectric) with transparent for MW signal electrodes. Simulation and experiments demonstrate that periodic structure provides the slow wave propagation effect, that in turn results in the increase of effectiveness of lens operation. At frequency ~ 30 GHz the lens provides scan angle $\alpha \sim \pm 20$ deg.

1. INTRODUCTION

The electrically scanning antennas are actively developing devices for telecommunication and radar system. Traditional solution of the beam antenna scan is the phased array antenna (PAA), which application in present time is becoming very actual in anti-collision car radars, in/out door communication systems, in space radars and etc. [1, 2]. One of the main disadvantages of mm wave PAA is a rather large MW losses in dividers and intrinsic feeders for the strip-line technology and very complicated and expensive construction in a case of the metal waveguide technology. In recent years electrically tunable lenses (ETL) becomes powerful beam-forming platform that can be used instead of phase array antennas. This approach allows the radical decrease of MW losses and greatly simplified design due to absent of dividers and intrinsic feeder lines. In a set of works the ferroelectric materials are proposed to be used as a base of tunable distributed elements of lenses [3–6]. According our knowledge there are no publications devoted to multilayer structure periodic in longitudinal plane (along direction of wave propagation). The use of periodicity in longitudinal plane allows to decrease of control voltages value and increase of scan angle in comparison with nonperiodic and transverse periodic analogues. The main parameters of the periodic lens were obtained by modelling and were confirmed by experimental testing of prototype lens at frequency ~ 30 GHz.

2. THEORETICAL PART

Basic concept and simulation results. The basic concept of ferroelectric ETL is described in [3, 6]. It consists of ferroelectric plate covered by high resistive electrodes, which are transparent for the microwave signal (Fig. 1(a)). ETL deflects the microwave beam in one plane for realization of 1D scan regime. The principle of operation of the device is as follows: application of different control voltages between ends of the top high resistive electrode leads to different E-field values between top and bottom electrodes along the FE plate, that in turn, results in the corresponding variation of the permittivity along the plate (see color density variation in Fig. 1(a)). The value of deflection angle α is determined by the difference of the signal phase shift values at opposite edges of the ferroelectric layer $\Delta\phi$ [4]:

$$\alpha = \arctan \frac{\lambda}{l} \frac{\Delta\phi}{2\pi} = \arctan \frac{d}{l} \left(\sqrt{\epsilon}(0) - \sqrt{\epsilon}(E_{\max})\right), \tag{1}$$

where λ — the wavelength in free space; l — the deflectors aperture size; d — the thickness of the ferroelectric layer; $\epsilon(E)$ — the permittivity as a function of control electric field.

Thereby, the higher deflection angle, for ETL with fixed aperture, can be achieved due to the increase of the lens thickness and/or the ferroelectric nonlinearity. However, both of these options lead to the increase of MW losses and values of the control voltage. Furthermore, in order to maintain any angle of beam propagation (except for $\alpha = 0$) the control current continuously flowing through high resistive electrodes is needed, that inevitably leads to the heating phenomena in FE plates.

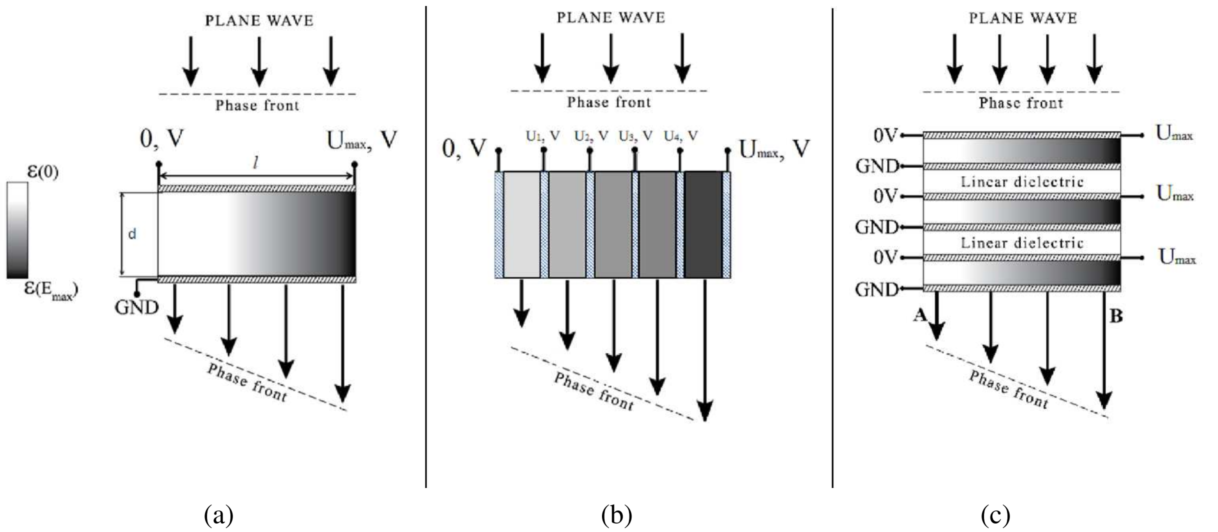


Figure 1: (a) One-layer and (b) multilayer ETL periodic in transverse and (c) longitudinal plane based on ferroelectric materials.

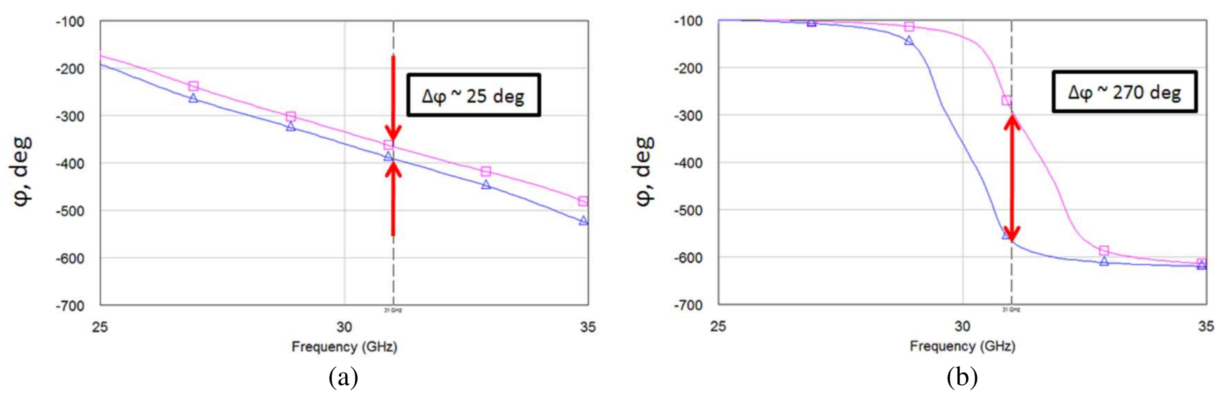


Figure 2: (a) Phase shift of one-layer and transverse periodic (classical) ETLs; (b) phase shift of periodic ETL.

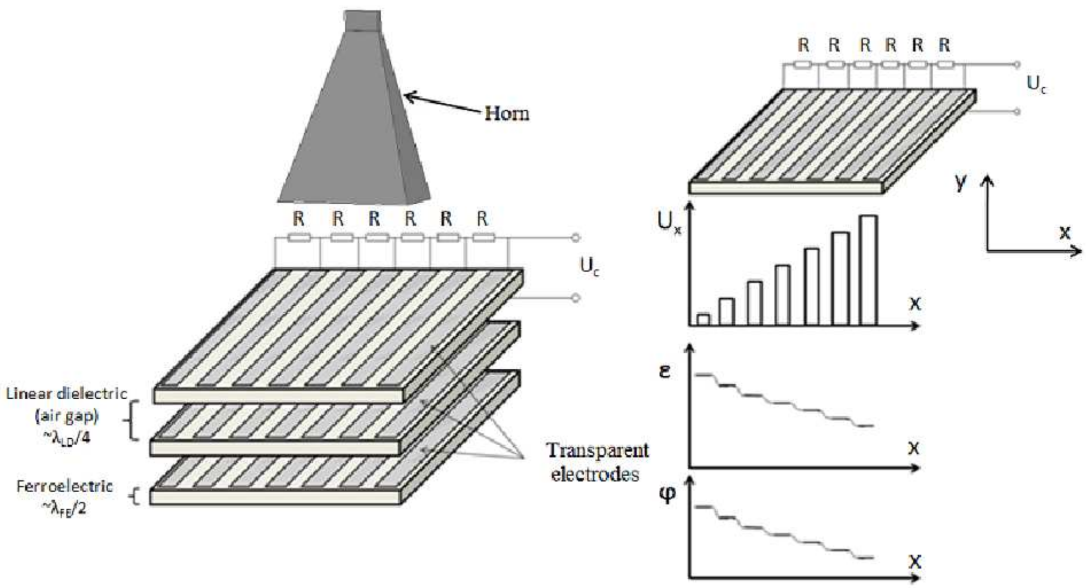
To solve the problems mentioned above the more complex designs of ferroelectric lenses were elaborated (Fig. 1(b)) [4, 5]. The main difference of ETLs proposed in [4, 5] in comparision with construction of Fig. 1(b) is the periodicity of their structure in the transverse plane relative to the direction of the wave propagation (Fig. 1(b)). However these constructions provide the possibility to decrease the control voltages, but do not result to the increase of the scan angle at the same sizes.

In present work the construction based on periodic in longitudinal plane structure is proposed (Fig. 1(c)). In contrast to the lenses presented earlier, the periodic structure of this lens provides the slow-wave propagation and has a passband characteristic. These properties allow to achieve the higher value of $\Delta\phi$ in comparison with classical approach described above. The distinctive feature of the deflector is the use of multilayer periodic structure FE/LD/FE/LD/.../FE (FE-ferroelectric, LD-linear dielectric) with transparent for MW signal electrodes.

The thickness of each ferroelectric layer is equal to $\lambda_{\rm FE}/2$ (($\lambda_{\rm FE}$) — the wavelengths in a ferroelectric material), while the thickness of the linear dielectric layer is $\lambda_{LD}/4$ ((λ_{LD}) — wavelengths in a linear dielectric). Thus ferroelectric layers can be considered as half-wave tunable resonators coupled by quarter-wave transformers. Ferroelectric layers are covered by electrodes transparent for microwave. Application of the same control voltages to ferroelectric layers leads to change of their permittivity, that results in tuning of structures passband to higher frequencies. The effectiveness of the proposed periodic structure is illustrated in Fig. 2, where the simulation results of the phase shift for periodic (Fig. 1(c)) and structures that shown in Figs. 1(a), (b). Note that the permittivity and the total thickness of FE layers of both structures are identical.

The tunability of ferroelectric material is $k = 1.1 (k = \epsilon(0)/\epsilon(E_{\max}))$. It is clear that for the our periodic structure the value of $\Delta\phi$ is an order of magnitude more in comparision with nonperiodic one. In accordance with (1) for lens with $l = 30$ mm that results to the radical increase of the scan angle from $\alpha \approx 1.3$ deg. (nonperiodic structures — Figs. 1(a), (b)) to $\alpha \approx 14$ deg. (periodic one — Fig. 1(c)). Thereby the use of the ferroelectric lens with proposed periodic structure allows to obtain higher performance of ETL at relatively low control voltages and ferroelectric nonlinearity in comparison with existed analogues.

The object for full wave analysis of lens in Ka frequency band is presented in Fig. 3(a). Lens consists of three FE layers and air gaps between them with the plane area of the structure of $30 \times 30\,\mathrm{mm}^2$. The step-like approximation to describe the distribution of the permittivity along the FE layers (x-axis) was used (Fig. 3(b)). In the experimental prototype the required distribution is provided by application of control voltages between the strips and continuous ground electrodes on top and bottom surfaces of each FE layer. Note that open-ended for control currents strip electrodes provide the non-heating regime.

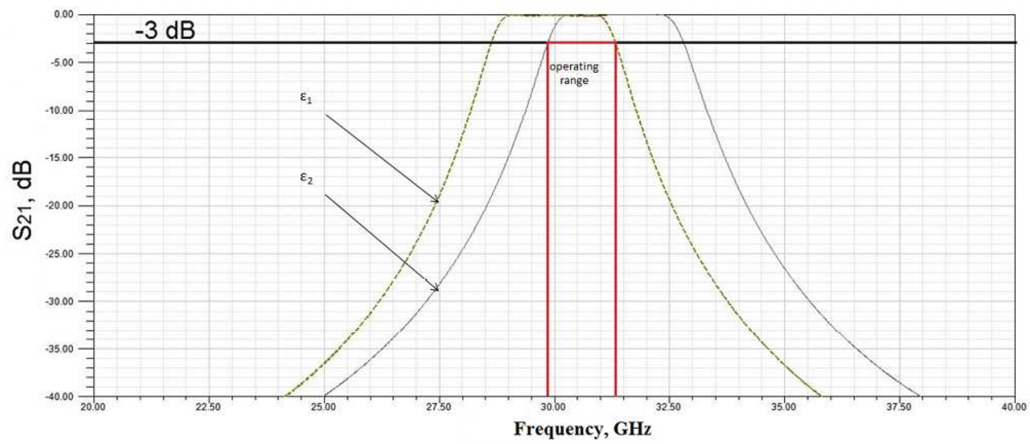


(a) (b)

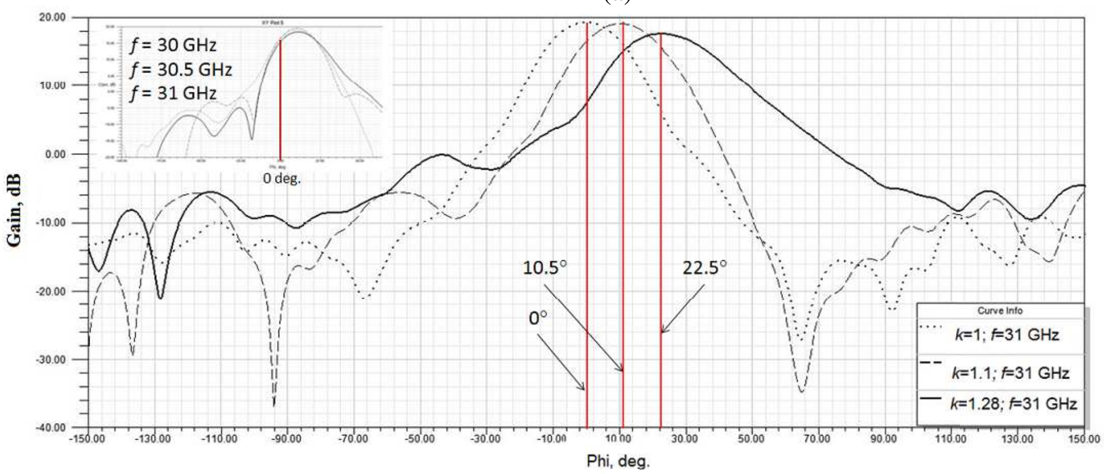
Figure 3: (a) Construction of electrically tunable lens based on periodic structure of ferroelectric layers; (b) single ferroelectric layer with corresponding step-like distribution of dielectric constant (ϵ) and phase shift (ϕ) under control voltage (U_x).

Values of electrical lengths for FE ceramic plates and air gaps are $\lambda_{\mathrm{FE}}/2$ and $\lambda/4$, for each media respectively. In accordance with theory of periodic structures and principles of the filter design these electrical lengths are the most effective to obtain required amplitude and phase parameters of scattering coefficients (S_{11} and S_{21}) for such structures [7]. The horn with aperture size equal to cross sizes of lens ($30 \times 30\,\mathrm{mm}^2$) is used as a source of the microwave plane wave.

Simulation results show that 9% change of dielectric constant (from $\epsilon_1 = 100$ down to $\epsilon_2 = 91$) of all ferroelectric layers leads to the tune of central passband frequency on the half of the bandwidth (Fig. 4(a)) that in practice has to characterize the bandwidth of lens as $\Delta f \approx 1$ GHz. Variation of ETLs beam pattern in condition of different distribution of ϵ along its plane (x-axis) is shown in Fig. 4(b). The step variations of ϵ_{FE} from 100 down to 91 (tunability $k = 1.1$) and from 100 down to 78 ($k = 1.28$) correspond to 10.5 and 22.5 degrees scan angle respectively in comparison with pattern for system with no variation of $\epsilon_{\mathrm{FE}} = 100$. The inset in Fig. 5(b) demonstrates the week dependence of radiation pattern on frequency in operation passband. Note that simulation is done for lossless electrodes and dielectrics elements of structure.



(a)



(b)

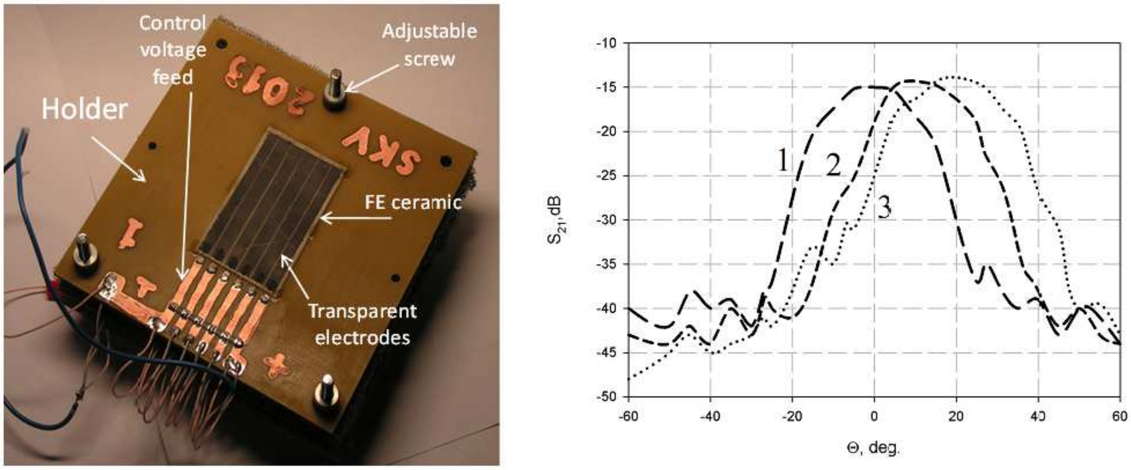
Figure 4: Characteristic of three ferroelectric layers periodic structure: (a) frequency dependence of transmission coefficient; (b) scan of lens pattern at different tunabilities of ceramic; variation of pattern at different operating frequencies (insert).

3. EXPERIMENTAL RESULTS

As a material for ETLs ferroelectric layers the ceramic of solid solution of barium-strontium titanate $Ba_xSr_{1-x}TiO_3$ with composition $x = 0.4$ was used. The permittivity of the ceramic is about 400. The thickness of each ferroelectric layer is 0.25 mm that corresponds to $\sim \lambda_{FE}/2$ electrical length at operating frequency 30 GHz. The tunability of material is about 2 ($k = 1.8$ at 10 V/μm). The microwave losses of ceramic in $30 \div 60$ GHz frequency range corresponds to $\tan\delta = 0.01 \div 0.02$. These values were estimated on the base of direct measurement of insertion losses (S_{21}) for 30 and 60 GHz signal passing through the single 0.25 mm ferroelectric plate without electrodes. The time-tunning response of the dielectric constant under unipolar pulse control E-field was not more than 1 μs [8] that is suitable for application of scan antennas.

To be a transparent for microwaves the lens electrodes has to be made from high resistive material. As a rule for similar applications the ZnO and Si-Ti-Ce composition with surface resistance up to 10 MOhm/square are used [9]. The value of insertion losses for one electrode layer of these materials with thickness ~ 10 nm is less than 0.2 dB at 30 GHz operating frequency. But in our proof of art experiments the simplest spray graphite technology is used. In accordance with our experimental data the graphite films with thickness ~ 10 μm demonstrate the surface resistance of $1 \div 2$ kOhm/square and at $f = 30$ GHz their additional microwave losses are about of 1.5 dB per graphite layer.

In Fig. 5(a) the photo of lens prototype installed in holder is presented. The lens with area of $30 \times 40\,\text{mm}^2$ consists of the periodic structure FE/Air/FE/Air/FE with graphite electrodes on the surfaces of FE plates. To fixate the ferroelectric ceramic plates in a space and to provide their correct separation by air gaps the special textolite holder with conductive traces for application of



(a) (b)

Figure 5: (a) Prototype of lens installed in adjustable holder; (b) scan of the radiation pattern at different gradients of the voltage distribution along the plate: (1) — zero voltage; (2) — (0(÷)400) V; (3) — (0(÷)800) V.

control voltages was designed. The horn with aperture diameter of 30 mm is used as a source of ~ 30 GHz quasi-plane wave for lens irradiation. The results of measurements of far-field radiation patterns at different control voltages are presented in Fig. 5(b). Experimentally observed scan angle $\alpha \approx 20$ deg. is in a good agreement with simulation one $\alpha \approx 22$ deg. (see Fig. 4(b)). Measured MW insertion losses of lens prototype is rather high (~ 15 dB) and is mainly determined by losses in graphite electrodes (~ 10 dB) and reflective losses (~ 2 dB) due to mismatching between horn and lens.

4. CONCLUSION

Simulation and experimental testing of the new construction of microwave (~ 30 GHz) electrically tunable deflector based on the ferroelectric periodic structure were done. The simplest three layer deflector prototype demonstrates the experimental scan angle $\alpha = \pm 20$ degrees. Taking into account no frequency dispersion of the dielectric permittivity of ferroelectric BSTO materials up to 100 GHz the tunable lenses on their base can be considered as not expensive, fast acting beam steer devices of mm and sub mm wavelengths.

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