Electrically tunable reflector based on ferroelectric material for millimetre wavelength range

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Abstract. The design of a millimeter-wave reflector based on the ferroelectric ceramic was elaborated and considered. Among the advantages of the proposed design are simplicity and cost-effectiveness compared to devices based on active repeaters and reflectarrays. The use of ferroelectric ceramic in the reflector design allows operating in a wide frequency range up to 100 GHz. Parameters of ferroelectric ceramic were experimentally measured and used in the electromagnetic simulation of the proposed reflector. Simulation of the reflector's radiation pattern demonstrated the effective beam scan possibility in a range of 35 deg.

1. Introduction

Due to the explosive demand for high-speed data transmission in wireless communication nowadays, millimeter-wave band carriers have become a wireless system trend. The active development can approve this statement of such innovative infrastructures such as the 5G network [1], WiGig network [2], “smart home,” and it’s a probable extension to the “smart city” [3]. The advantage of millimeter wavelength range use is a significant increase in the transferred information. At the same time, the main drawback is power consumption due to significant attenuation of electromagnetic waves in free space [4]. One of the main hindrances for mm-wave networks' effective coverage is line-of-sight (LoS) blockage. The main solutions to avoid this issue are active repeaters [5] and reflectors [6].

The use of a passive metallic reflector is the simplest way to improving mm-wave propagation in non-line-of-sight (NLoS) areas [5]. This solution can be attractive due to the large life span and low cost. Passive metallic reflectors have been used in past for microwave links for long-distance communications (such as satellite communications) and point-to-point microwave links. However the main drawback of the passive reflectors is the dependence of output radiation on transmitter antenna directivity and its angle of incidence on the reflector, in other words, it is not allowed to rearrange antenna radiation pattern without mechanical steering. In the case of indoor communications, the multifocal reflectors can be used to avoid this issue. But in outdoor communication systems, the use of tunable reflectors with the possibility of beam scan is more attractive. As a rule, such tunable reflectors based on actively phased elements that are operating in reflection mode [7]. In the construction of such reflectors, tunable elements like pin-diodes, varactors, etc. are commonly used [8,9]. This technical design is very useful in the microwave range, but difficult to implement at operating frequencies of K-band and higher [10]. The overcoming of the mentioned limitations is possible by using distributed nonlinear elements like ferroelectric (FE) ceramic plates as the base for...
tunable reflector design. It is well known that FE materials demonstrate a strong dependence of permittivity on an electric field value, that in combination with the absence of permittivity dispersion in the broad frequency range (up to 100 GHz), allowing to consider FE as a promising material for the use in the electrically controllable reflector.

This work describes the proposed design of an electrically controllable reflector on the base of ferroelectric ceramic plates, its principle of operation, and provides the results of full-wave electromagnetic simulation.

2. Principle of operation
In contrast to mechanical system, where orientation of reflector is variates to source antenna, the ferroelectric (FE) reflector is not moving. The direction of beam reflection electrically controled by the variation of FE permittivity. It is well-known that FE demonstrates dependency of permittivity ($\varepsilon_{fe}$) on the applied electric field ($E$). Measured dependence shown below, in corresponding section. Since permittivity and thickness of FE plate affects the phase of reflected wave for realization of the deflection of the reflected beam one should provide the spatial distribution of FE permittivity along reflector aperture. The aforementioned spatial distribution is not arbitrary and generally determined by required flatness of the reflected wave front and character of $\varepsilon_{fe}(E)$ dependence. The relation between the phase of outgoing wave and permittivity can be estimated from assumption of electrical equivalent circuit of FE plate.

Schematically the deflection of the reflected wave is presented in figure 1. The wave radiated by the source antenna incidents on FE reflector and reflects by a metalized grounded layer of FE plate. One can see that the permittivity of FE is varied along the reflector's aperture; thus, the wave obtains the different phase shifts at different parts of the FE plate. It should be noted that the variation of $\varepsilon_{fe}$ on the electric field is characterized by the tunability factor ($K=\varepsilon_{fe}(0)/\varepsilon_{fe}(E\neq0)$). The $K$-factor is more convenient for generality because of the possible specific of $\varepsilon_{fe}(E)$ curves of different ferroelectric materials. One can obtain the phase shift of reflected wave caused by electrical control of FE permittivity:

$$\Delta \text{Phase}(K) = \frac{4\pi \sqrt{\varepsilon_{fe}(0)d_{fe}}}{\lambda_o} \left(1 - \frac{1}{\sqrt{K}}\right)$$

This relation allows defining distribution of $K$-factor along reflector aperture to provide the required wavefront of outgoing wave based on main parameters of FE plate such as thickness and $\varepsilon_{fe}$ in the absence of electric field. With specific dependence of permittivity on the electric field, obtained $K$-factor distribution can be transformed to the distribution of control voltages ($U_i$ in figure 1) applied on each FE plate section.
To realize the control over FE permittivity, one should provide control electrodes in the lens design. The control electrodes should correspond to several requirements, such as low insertion loss, simple implementation, and minimizing the heating of the FE plate caused by the electric current (Joule heating). It is much more convenient to use radiotransparent electrodes based on a thin film of the high resistive materials instead of metal electrodes were used in [11,12]. The different materials used for the fabrication of thin-film planar resistors also can be a perspective for this purpose in the microwave and millimeter-wave ranges.

The discrete topology of the control electrode consists of the discrete sections of a radiotransparent material was used in the FE reflector design proposed in this article. The electric potential applies to each section of the electrode. In such a configuration, each electrode section is an open-circuit for the control voltage and, therefore, the electric current is not flowing through it. There is the restriction on the width of the electrode section for this type of electrode topology, it should be less than half of the operating wavelength in free space. This restriction was considered in [13] in more detail.

3. Ferroelectric material

As mentioned above, the design and analysis of an electrically tunable FE reflector are better to consider the measured dependence of $\varepsilon_{fe}(E)$ due to this dependence's nonlinear character and possible variation for different FE materials. For the experimental investigation, the ceramic samples of a solid solution of Ba$_x$Sr$_{1-x}$TiO$_3$ (BSTO) were used. The BSTO is a well-known ferroelectric material. Its properties in the paraelectric state, such as fast time response, low dissipation loss, and the absence of permittivity dispersion, allow considering BSTO a promising material for applications in the millimeter-wave range [14,15]. The characterization of FE nonlinearity is provided by capacitance-voltage CV dependency measurements of FE capacitors under dc control voltages resulting in a tunability factor $K=C(0)/C(U_{dc})$. The FE ceramic capacitors were fabricated with $5\times5$ mm$^2$ contact copper metallization deposited on the opposite sides of the ceramic plate. The obtained experimental results of permittivity and tunability dependencies on the electric field are presented in figures 2a and 2b correspondingly. To provide high precision measurements of ceramic tan$\delta$ the electrodeless method based on an open resonator (OR) was used. In accordance with the described measure technique, the loss tangent value of the ferroelectric ceramic plate was about 0.015–0.02 at 60 GHz.
4. Simulation results

The Radio Frequency module (Electromagnetic Waves, Frequency Domain interface) of the COMSOL Multiphysics software was used to perform the 2D electromagnetic simulation of the FE reflector device to prove the proposed beam deflection concept. The region of numerical simulation is presented as an air-filled circle of a radius of 50 wavelengths at 60 GHz with radiation boundaries containing a waveguide flaring to a horn (source antenna) and a ferroelectric plate with impedance matching layer. One side of FE plate was assigned as perfect electric conductor (PEC) boundary to provide reflection of the incoming wave. The horn dimensions were calculated based on the procedure described in [16]. The reflector model consists of ferroelectric plate with quarter wavelength matching layer of linear dielectric. The overall size of the FE lens aperture is $11\lambda_0$ (at 60 GHz) with a total thickness of the FE plates 2 mm. The FE plates were divided into 22 rectangular regions to provide the discrete spatial distribution of phase shifts. The permittivity of each region is determined as $\varepsilon_{fe}/K_i$, where $\varepsilon_{fe}$ – ferroelectric permittivity without control electric field ($\varepsilon_{fe} = 440$) and $K_i$ – tunability factor corresponded to the $i$-th FE region. According to measured tunability of ceramic samples and relation (1) the values of $K$ for each FE plate section was defined to provide plane wave deflection in specified angles.

The simulation results of the wave E-field distribution corresponded beam reflection and deflection are presented in figure 3 correspondingly. The presented E-field distributions clearly demonstrate the flatness of the outgoing wave. The effectiveness of the proposed reflector can be concluded from the simulation results of radiation patterns presented in figure 4. It demonstrates that the achievable scan angle is in range of 35 deg. with side lobes below -14 dB.

Figure 3 Distribution of reflected wave electric field in the cases of zero control voltage – a) and non-zero control voltage distribution in ferroelectric plate.
5. Conclusion

The design of an electrically tunable reflector based on ferroelectric ceramic was considered and analyzed. Parameters of reflector design were estimated for 60 GHz operating frequency. Full-wave analysis based on experimental measurement results of ferroelectric ceramic was performed. The obtained results demonstrate the quality of wavefront flatness of the deflected wave. According to simulation results, the beam scan range is about 35 deg. The proposed reflector design can be useful for millimeter-wave wireless communication systems to avoid LoS blockage.

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