Tunable microwave filters with controlled ferroelectric capacitors

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Tunable Terahertz Metamaterials Based on Electrically Controlled Piezoelectric Actuators¶

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Abstract—A new concept of tunable terahertz metamaterial with electrically controlled characteristics is suggested. Two versions of creating tunable metamaterials using piezoelectric cantilevers as controllable elements are designed. Configurations of tunable metamaterials designed as planar metal–dielectric structures of arrays of U-shaped resonators and square metal patches with piezoelectric actuators are proposed.

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Recently, the possibilities of designing devices and their applications for the terahertz frequency range, particularly in medicine and security systems, have been investigated. This is due to the fact that terahertz radiation can easily penetrate into biological objects and, at the same time, this radiation is safe for human health. Artificial materials referred to as electromagnetic metamaterials can be used for development of functional devices for the terahertz frequency range. This class of artificial composite materials is characterized by extraordinary electromagnetic properties, such as negative permeability or/and permittivity and negative refraction coefficient. Controlling these properties allows terahertz devices to be designed with tunable technical characteristics: operational bandwidth, insertion loss, and sign and value of the effective electromagnetic parameters.

Control of metamaterials can be achieved by using ferroelectrics [1], semiconductors [2], and liquid crystals [3]. Using MEMS for effective control of the properties of metamaterials in the terahertz region is also promising [4].

Metamaterial based on split ring resonators (SRRs) is a widely used type of metamaterial. Different modifications of metamaterial using SRRs are presented in [5, 6]. Tunable metamaterials with SRRs are usually formed via tunable capacitance or conductivity in the gap of the ring [1–4].

A U-shaped resonator is a modification of an SRR [7]. It is a half-wavelength resonator consisting of three metal strips, two of which are perpendicular to the first one, forming the letter U (Fig. 1a). The dimensions of the resonator and dielectric permittivity of the substrate are chosen so as to provide a resonant response in the appropriate frequency range. In the terahertz region, the length of the resonator is about 100 μm. For simulation, the width and length of the horizontal and vertical metal strips are taken to be 40 and 120 μm, respectively. The thickness and the dielectric permittivity of the substrate are $h = 40$ μm and $\varepsilon_r = 2.5$, respectively. The directions of electric field E and magnetic field H are shown in Fig. 1a. The maximum of E is achieved at the ends of the U-resonator at the resonant frequency (Fig. 1d). The resonant frequency of the first mode is 0.384 THz. The resonant frequency of the U-shaped resonator can be tuned by embedded controllable cantilevers using piezoelectric materials (Fig. 1b) [8]. Tunable piezoelectric cantilevers are commonly used in the microwave frequency range [9], but can be easily scaled to the terahertz range using processes of modern microtechnology.

Under biasing voltage or temperature variation, the cantilever bends at the angle α. As a result, the electric field is concentrated in the formed gap (Fig. 1e) and a tunable capacitance occurs, giving rise to a change in the electrical length of the resonator. This, in turn, results in a shift of the resonant frequency. Control of actuators is provided by metal strips with biasing voltage. The results of full-wave simulation of a metamaterial structure with U-shaped resonators on dielectric substrate are presented in Fig. 1c. If the angle α changes from 0° to 15°, the resonant frequency varies from 0.384 to 0.586 THz (Fig. 1f). The designed metamaterial can be used as a tunable band-stop filter in the terahertz frequency range. The advantages of this structure are high speed and efficiency of frequency tunability.

The other type of metamaterials is the metal–dielectric–metal (MDM) structure implemented as metallic patches on both sides of the dielectric substrate [10, 11] shown in Fig. 2a. Two metallic patches form the capacitance. The circulating current on patch surfaces produces the magnetic resonance

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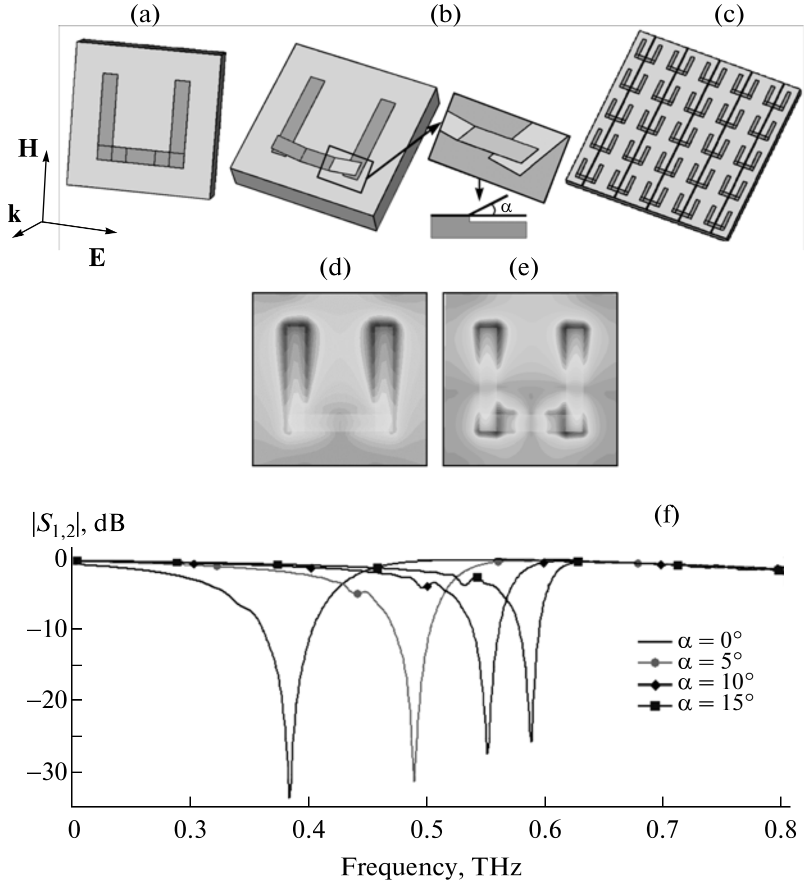

Fig. 1. U-shaped resonator (a) with cantilever bending at the angle α (b) and distribution of **E** at the resonant frequency at α = 0° (d) and α = 15° (e). Array of the U-shaped resonators (c) and frequency dependence of the transmission coefficient of the array at different values of the angle α (f).

response [11]. The surface current distribution in a unit cell of two coupled metallic patches is shown in Fig. 2b. If one of the metallic patches is removed, the resonant response in this frequency range will disappear. The transmission spectra of a single patch and the coupled patch pair are shown in Fig. 2c.

The resonance frequency of the MDM patch array depends on the value of the capacitance between two coupled patches. If the part of the patch metallization is flexed up, the distance between the patches is changed, with the capacitance changing as well and providing a shift of the resonant frequency. When the angle between the bent part of the patch metallization and the substrate is increased, the capacitance is decreased and the resonant frequency is shifted to higher frequency.

Simulation of the transmission coefficient has been done for the MDM patch array with piezoelectric cantilevers (Fig. 2d). The cross section of the MDM structure with a piezoelectric cantilever is similar to the experimentally investigated cantilever in [12] and is shown in Fig. 2e. Movability of the cantilever is provided by etching the layer of silicon substrate. The layer of SiO_2 is used as a membrane for improvement of the elasticity of the structure. The piezoelectric element produces curvature under applied dc-voltage between the electrodes due to the strength of internal compression. All piezoelectric cantilevers at one side of the substrate are connected together by the biasing bus for controlling their bending angle. The biasing bus is parallel to the magnetic component of the electromagnetic field for preventing interaction with incident terahertz radiation. The thickness of metallization is 200 nm. High-impedance silicon with 20 μm thickness and dielectric constant ε = 12 with tan(δ) = 0.001 is used as a substrate. The width of the patch is 200 μm, and the distance between the patches is 100 μm. The width of the biasing strip is 20 μm. Full-wave simulation results of transmission spectra for different angles of the cantilevers are shown in Fig. 2f. The amplitude–frequency characteristic of this structure corresponds to low-pass filter response with tunable cutoff frequency. The tunability of the cutoff frequency is 24% for the bending of the movable part of the piezoelectric actuator with respect to the substrate at angle α from 0° to 10°.

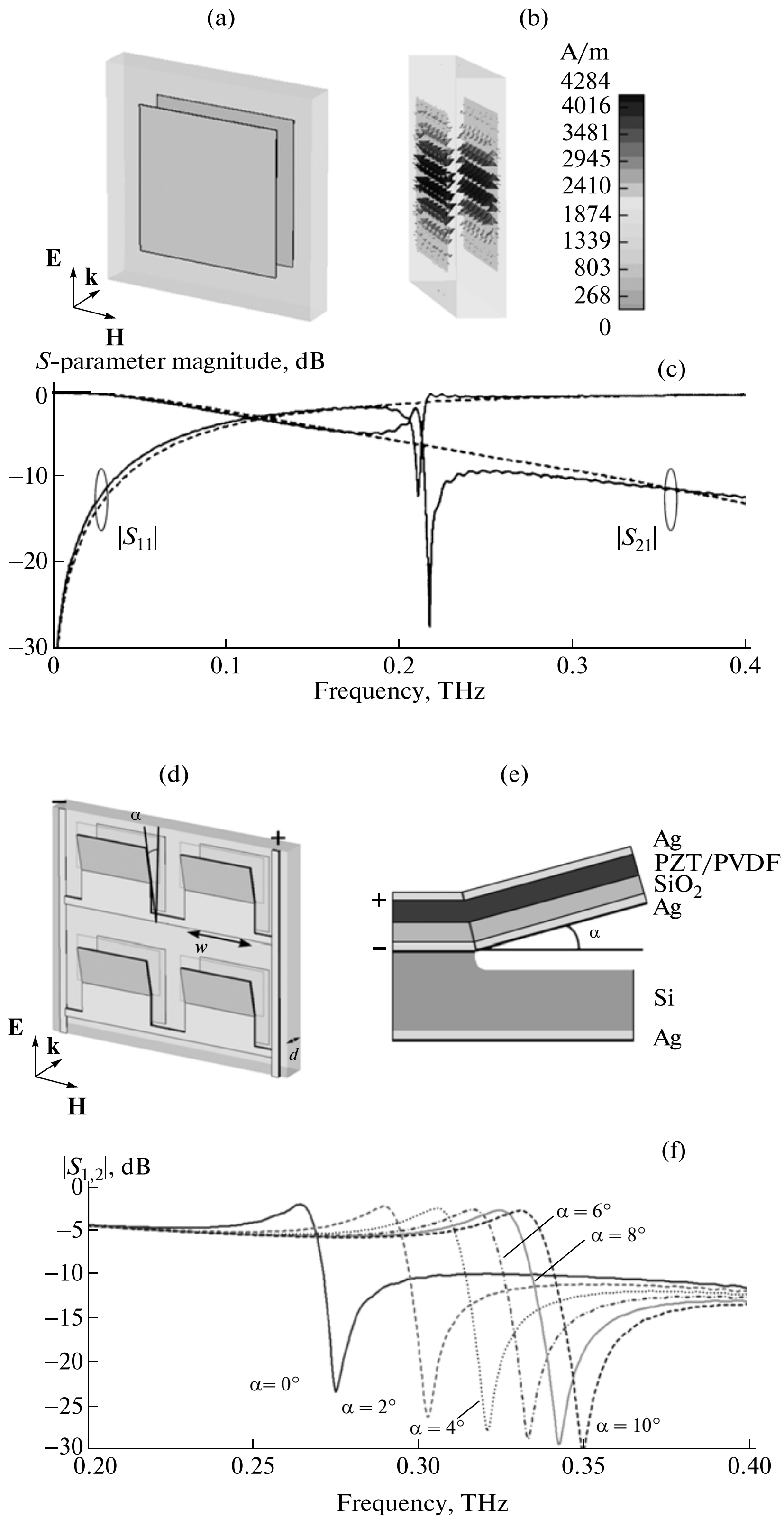

Fig. 2. MDM structure based on coupled metallic patches: unit cell (a), surface current distribution at the resonant frequency in the unit cell (b), transmission and reflection coefficient for the unit cell with one patch (dashed line) and for two coupled patches (solid line) (c), patch array formed by a four-unit cells with a piezoelectric actuator and biasing bus (d), cross section of the unit cell with a piezoelectric cantilever (e), and transmission coefficients for a patch array with different bending angles of the actuator α (f).

It has been proposed to use PZT (Pb(Zr,Ti)O_3) or PVDF $(CF_2{-}CH_2)_n$ in β-form as piezoelectric materials in actuators. The crystalline polymer PVDF with a high elastic property can be used for excluding the membrane layer from the cantilever structure. Samples of actuators based on the proposed piezoelectrics were experimentally investigated in [8, 12, and 13].

The efficiency of the piezoelectric actuators can be increased by using two piezoelectric layers with different signs of piezoelectric constant. In this case, cantilever bending is provided by both compression and tension. The extent of the actuator bending can be further increased by increasing the length of the movable part or reducing the thickness of the actuator.

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