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STUDY OF CONTROL INHOMOGENEITIES OF THE DIELECTRIC BETWEEN METAL PLANES OF MICROWAVE DEVICES IN PHASED ARRAY ANTENNAS

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Abstract. *This article describes the phase shifters, based on micro-electromechanical elements connected to phased array antennas which operating in the frequency range 2–30 GHz. Estimations of controllability characteristics located between the metal dielectric planes, heterogeneity as an element of a micromechanical controlled microwave-devices. It is shown that when microdisplacements metal plane above the dielectric effective permittivity inhomogeneities it may vary from the values of the relative permittivity of the dielectric to one unit. Criteria required is small dielectric thickness or frequency at which the dielectric effect is not observed. The results can be used in the design of electromechanical devices managed using the MPN of piezoelectric and electrostrictive actuators or MEMS.*

Keywords: micromechanical management, effective permittivity, dielectric heterogeneity, MEMS phase shifter

BADANIE ZAKŁÓCEŃ STEROWANIA DIELEKTRYKA MIĘDZY METALOWYMI PŁYTKAMI W URZĄDZENIACH MIKROFALOWYCH ANTENOWEGO SZYKU FAZOWANEGO

Streszczenie. *W artykule opisano przesuwniki fazowe na bazie elementów mikro-elektromechanicznych podłączonych do antenowego szyku fazowanego, pracującego w zakresie częstotliwości 2–30 GHz. Dokonano oszacowania cech sterowalności heterogenicznego dielektryka położonych pomiędzy metalowymi płaszczyznami, jako elementu mikromechanicznie sterowanego urządzenia mikrofalowego. Wykazano, że gdy przy mikro-przemieszczeniach metalowa płytki nad dielektrykiem niejednorodności przenikalności skutecznej mogą osiągać wartość 1. Wymagane kryteria to mała grubość dielektryka lub częstotliwość, dla której nie obserwuje się wpływu dielektryka. Wyniki mogą być stosowane przy konstrukcji urządzeń elektromechanicznych sterowanych za pomocą siłowników piezoelektrycznych, elektrostrykcyjnych lub MEMS.*

Słowa kluczowe: zarządzanie mikromechaniczne, przenikalność efektywna, heterogeniczność dielektryka, przesuwnik fazowy MEMS

Introduction

Microwave phase shifters find uses in many communications circuits, and for several applications, such as phased antenna arrays, phase shifter loss directly impacts the signal's dynamic range. Moreover, the large size and high cost of ferrite based phase shifters that are dominant in antenna arrays prevent widespread use of phased-arrays in public communication and related industries. Microelectromechanical system (MEMS) circuits have the potential to be inexpensive, have low loss, and have high quality phase-shifting capability. They can also be integrated circuit (IC) compatible, and are thus harmonized with the quest of achieving integrated and ever smaller radio frequency (RF) front ends.

The main advantage of tunable microwave devices with electro-mechanical control is low insertion loss and maintaining a high quality factor. However, such devices have a high controllability. Since the resonant frequency of the oscillation of the lowest type of dielectric resonators with transverse inhomogeneity rebuilt by 25–30%. Electromechanical phase shifters based on microstrip and coplanar transmission line provides a phase shift in the hundreds of degrees at intervals equal to the wavelength.

Electronically Scanned Arrays (ESAs) or phased array antennas use electronic, mechanical, or material switches to alter the phase of individual radiating elements across an antenna, and in so doing, enable the radiated beam to steer [3]. Communication and radar systems incorporating phased arrays will enable greater efficiency, higher data rates and increase access between greater numbers of links.

Electrotechnical managed devices, usually composed on the basis of movement of dielectric or metallic parts relative dielectric. Designing these devices due to the optimum choice of material and size of dielectrics in terms of the possibility of transfers required and necessary management characteristics [3].

In this paper we investigate the simplest element of control devices – dimensional dielectric heterogeneity, which is placed between the ideal metal planes – from the point of view of increasing the efficiency of management.

1. The dispersion characteristics of dielectric heterogeneity between the metal planes

Consider a one-dimensional structure consisting of dielectric inhomogeneities, which is placed between the ideal metal planes. Electromagnetic oscillations in the considered structure laid out fluctuations LM and LE-type, non-independent solutions of Maxwell's equations. The transverse wave number LM-modes is found from the condition of continuity of the tangential components of the electromagnetic field in the plane y = h [5]:

$$\frac{\beta_{y1}}{\varepsilon_1} tg\left(\beta_{y1}h\right) + \frac{\beta_{y2}}{\varepsilon_2} g\left(\beta_{y2}h\right) = 0\,,$$
$$\left(\varepsilon_1 - \varepsilon_2\right)k^2 = \beta_{y1}^2 - \beta_{y2}^2 \tag{1}$$

where β_{y1}, β_{y2} is the transverse wave numbers in area 1 ($1 \le y \le h$) and in area 2 ($h \le y \le h + d$); $k = \omega / c$ is the propagation constant in free space; ω is the angular frequency; c is the speed of light in vacuum.

The solution of the dispersion equation (1) depends only on the frequency, the dielectric constant and the size of areas 1 and 2 in Fig. 1 [8]. The normalized first roots of these equations for different values of the relative permittivity of the region 1 and the various normalized propagation constants of the free space *kh* are shown in Fig. 2.

There are two types of MEMS switches: capacitive and metal-to-metal contact switches. Capacitive switches, as shown in Fig. 1, employ a thin insulator between the transmission line and the cantilever to prevent the two metal structures from touching. Thus, when the switch is in the up state, a very small capacitance due to the 3 to 5 micron of air gap has very little effect on the electrical signal. However, when the cantilever is in the down state, one has a very large capacitance. It results in an effective short circuit at high frequencies due to the thin insulator, which reflects the electrical signal. Because capacitive switches rely on a change in capacitance, they are ineffective at low frequencies, but virtually no direct current flows in the bias circuit of capacitive switches. Metal-to-metal contact switches are often fabricated as series switches that has a gap in the transmission line that prevents signal propagation when the switch is up, and when the switch is pulled down, a metal bar completes the circuit. Because the metal contacts are resistive, the insertion loss of these switches increases with frequency. Thus, these circuits are effective from DC to microwave frequencies, but they are not effective at millimeter-wave frequencies.

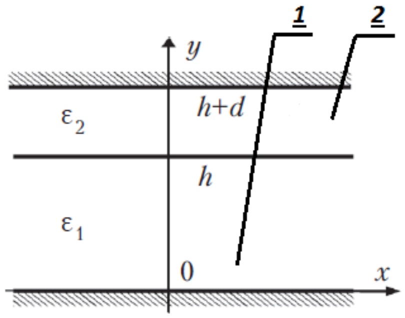

Fig. 1. Dimensional structure of the electrical inhomogeneity

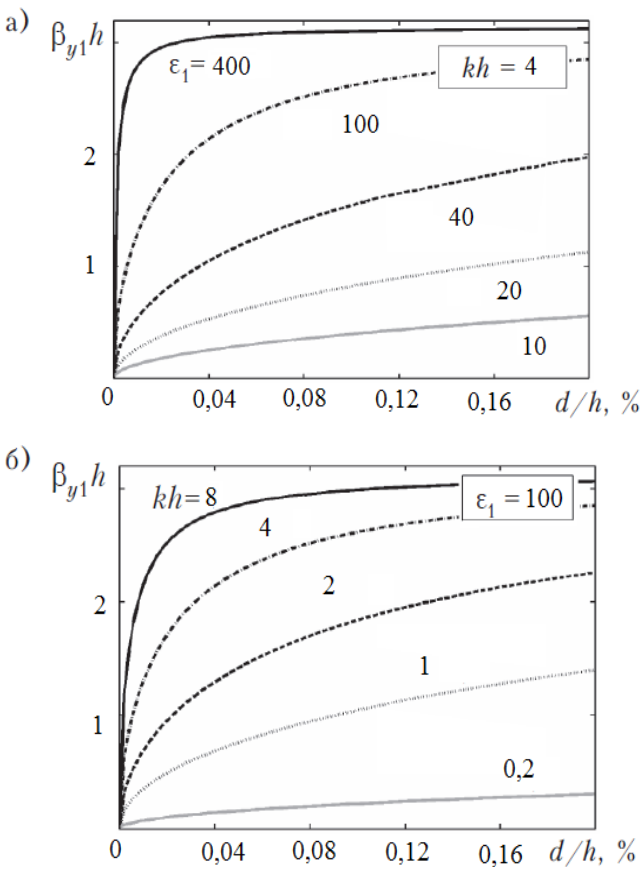

Fig. 2. Plots of normalized transverse wave number in LM-vibration 1 for low-oscillation of the normalized thickness of the air gap (ε_2 = 1) at different ε_1 (a) and kh (б)

As show in Fig. 2, in the case when the area 2 is an air (1), on the transverse wave number of oscillations LM-vibration strongly influenced by the distance *d* from the dielectric permeability of a metal plane ε_1. Change this distance only in a few hundredths of a percent of the thickness *h* and the dielectric's leading significant change in the transverse wave number. Quantitatively, these changes increase with increasing the permittivity region 1 and frequency [2].

As show in Fig. 3 oscillation LE-type characteristic of much smaller quantitative changes transverse wave number than the LM-type changes required field 2 sizes to achieve these changes are commensurate with the size of the dielectric in the field 1 [6]. Therefore, micro mechanically tunable device can not be constructed on the basis of LE-vibration.

Unlike LE-vibration LM-oscillation has a component E_y of the electric field perpendicular to the plane of the dielectric inhomogeneity. Therefore, for the effective restructuring of the electrodynamics properties of dielectric structures air heterogeneity it should be positioned perpendicular to the electric field. Similarly, we can show that for an effective restructuring of magnetic materials is possible in the presence of components of the magnetic field perpendicular to the air heterogeneity.

Since LE-types of oscillations have low maneuverability and can not be used for micromechanical management in the future we will consider only the lowest LM-vibration, which are the main type of vibration and have the highest sensitivity of the change of the air gap between a metal and an insulator, as well as the lowest critical frequency.

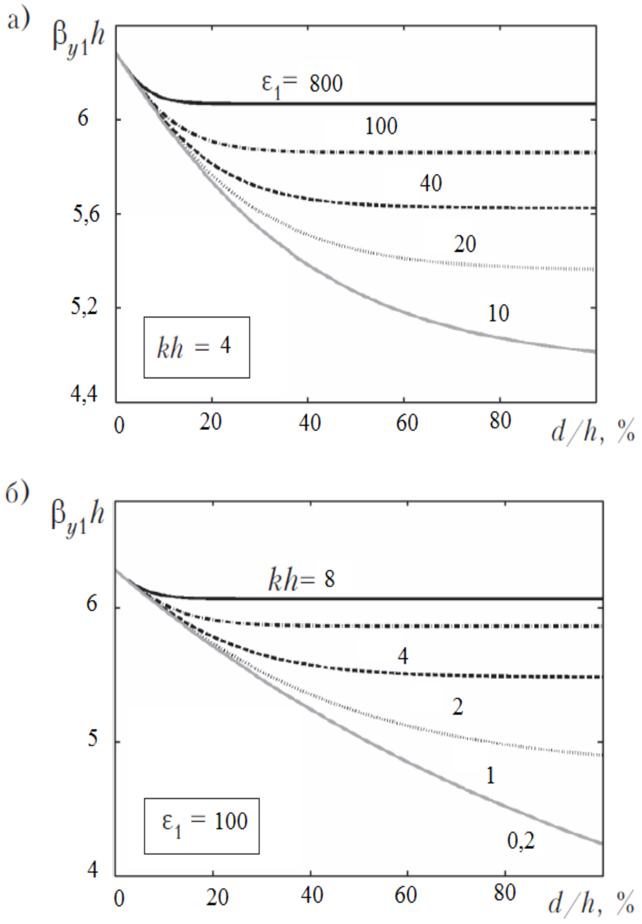

Fig. 3. A plot of normalized transverse wave number in the 1 for lower LE-vibration after-oscillation of the normalized air gap thickness (ε_2 = 1) at different ε_1 (a) and kh (б)

2. The results of experimental studies of microstrip structures

Rotating type RF MEMS switch and a metal contact cantilever beam switch [2, 7] for microwave frequency circuits were first demonstrated in 1991. At the present time, all MEMS switches embedded within microwave transmission lines operate as reflective switches, or devices that create a loading condition that causes the electrical signal to be reflected back in the direction from which it came. Furthermore, only metal cantilever type switches are being reported. In general, these switches consist of a single or double supported metal cantilever suspended over a microwave transmission line and bias circuit. In its up state, the cantilever is several microns above the circuit, but if an electromagnetic force is applied between the cantilever and bias circuit, the cantilever is pulled down and interacts with the circuit. Because the electromagnetic force is always attractive, the 10 to

50 V bias voltage may be applied to the transmission line or the cantilever and it may be either 2 positive or negative voltage, but this also means that the return of the switch to the up state relies on the restoring force of the metal.

By the magnetic active media include ferrites, and thin magnetic films. The ferrite plate is, as a dielectric, can be used as the substrate of the microstrip line (Fig. 4a), which allows controlling the parameters of the microstrip line. The ferromagnetic film, which lies in a plane perpendicular to the lines of the electric field in the microstrip structure, and having a thickness smaller than the skin depth at the working frequency, is practically not exhibit its conducting properties and can be used as a medium with a high magnetic permeability, depending on the external magnetic field. Due to the small thickness of such a film (hundreds of nanometers in a centimeter range), the duty ratio of the line active material is small, and to enlarge the use of multilayer structures made of ferromagnetic films separated by dielectric layers (Fig. 4b) [4].

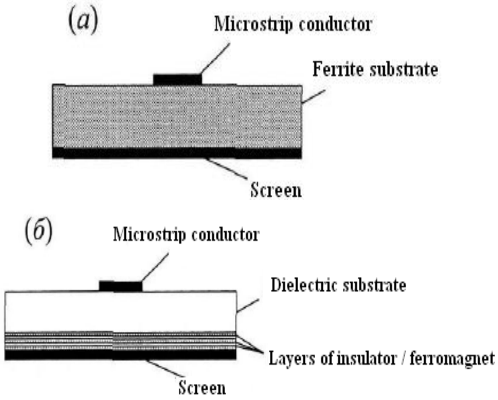

Fig. 4. Cross section of microstrip lines with active media in the form of ferrite (a) and a multilayer TMF (б)

The behavior of the transmission line characteristics due to the phenomenon of ferromagnetic resonance (FMR) is difficult to depend on the strength of the external magnetic field and its orientation relative to the magnetic field of the microwave. The measuring cell was coordinated with a path segment microstrip transmission line insulator in the central part of which was removed, and the microstrip conductor formed on the ceramic substrate inverted. Instead, the remote site can be inserted with the substrate deposited on it FRM [7]. The distortions introduced by a film in the frequency and phase response line, restated its effective parameters - frequency-dependent magnetic permeability and magnetic losses. The technique allowed the study, behavior of the parameters of the microstrip line, depending on the film material, the number of its layers, the direction of the easy axis (DEA), and the external magnetic field [1].

3. Designing MEMS-nodes

The peculiarity of RF MEMS components is extremely small distances between conductors carrying the microwave signal of the need for careful consideration of the mechanical and electrical properties of the materials used in the closest connection of three-dimensional design. It is combined with the technological capabilities of its manufacture, to accommodate the plurality of electrodynamic parameters of interaction of closely spaced nodes and conductors. Therefore, the role of specialized software development tools MEMS components cannot be underestimated. The most well known software packages designing RF MEMS devices (COVENTOR [4], VeloceRF, ANSYS, SUGAR, FEMLAB, Momentum ADS, CST Microwave Studio) support the analysis of electrostatic effects in two- and three-dimensional inhomogeneous medium with losses. They make it possible the calculation of the thermomechanical parameters and transients given hysteresis, thermal deformation, elastic effects; effects associated with packaging the product into the housing. Its are recalculation of the phenomena on the level of electromagnetic fields to the level of distortion waveform and vice versa, as well as a three-dimensional analysis of the electrodynamic fields in inhomogeneous media with losses. The packages usually include a module design and structural concepts with the use of behavioural models of electromechanical and microwave devices, as well as the standard of radio. Of course, also are needed library materials parameters; editors layered topology describing two-dimensional podistem and combining them into a three-dimensional structure; emulator available technological processes with the introduction of the set of its parameters; results visualization module. Design of MEMS-site "from scratch" takes an average of about seven days. Specifying another iteration it would require from several minutes to several days. With this approach, the full cycle of designing devices based on MEMS site takes about three months.

The band - phase shifter design utilizes one-bit sections of switched delay lines on microstrip and a resistive biasing network. Fig. 1 shows a schematic of the -band 4-bit phase shifter. Fig. 2 shows a similarly developed 3-bit phase shifter. Both designs are built on 6-mil high-resistivity silicon and feature wireless topology using resonant stubs as virtual RF grounds. By switching in different lengths of transmission line, phase shifts relative to the zero state or “reference” state are obtained. The switching is done using shunt RF MEMS capacitive coupled switches. To turn off a section of line, two quarter-wave transformations occur from the tip of the resonant stub to the tee junction on the RF signal trunk line. The first quarter-wave transformation is from the end of a quarter-wave stub to the centre of the RF MEMS switch. The end of the stub is an open so the centre of the switch becomes a short at the desired frequency. The second quarter wave transformation is from the centre of the switch to the tee junction. This transformation translates the short at the centre of the switch to an open at the tee junction. These lengths are not physically a quarter wavelengths because the capacitive effect of the RF MEMS switch. The length of the line was optimized to account for the change in phase velocity. Because the RF signal sees an open at this point, the signal travels down the desired path. Because all these quarter wave transformations depend on there being a 90 phase shift, this is a resonant design. By designing quarter wavelengths for the target frequency, you can easily obtain over 5% of bandwidth.

Each bit in this configuration is designed in the same fashion. There are two paths created. One is the reference path, and the other is made to be a certain length longer corresponding to the desired phase shift. In this case, the first bit has 180 of extra line length in the delay path compared to the reference path. Thus, when the switches are actuated in the reference path, the signal propagates through the delay path and travels 180 further than in the reference path. A similar design procedure is followed in the subsequent bits. The next bit’s delay path is 90 longer than the reference, then 45 and then 22.5 each bit is then cascaded together. The result is a resonant phase shifter that shifts from 0 to 337.5 in 22.5 steps. The three-bit phase shifter is the same as the four-bit variety except that the 22.5 bit is omitted.

4. Summary

Thus, for effective control of dielectric characteristics due to change inhomogeneity distance from the plane of metal necessary to use dielectric LM-vibration feature is the presence of an electric field component perpendicular to the boundary "air-dielectric" section. Changing the size of the air heterogeneity leads to a strong electromagnetic field disturbance and, as a result, the dispersion characteristics change. The required movement to create tunable devices comprises a few percent of the thickness of the dielectric and is available for advanced piezoelectric, electrostrictive actuators and microelectromechanical systems.

With sensitivity to the resonant frequency of a resonator, parameters can be qualitatively and quantitatively assess the impact of each option to change the cavity resonance frequency. Depending on the presented sensitivity of resonant frequency to change air gap shows that the most effective change in the resonance frequency is achieved when air spaces that correspond to tens of percent of the height of the substrate crystal. These microscopic movements can realize the proposed method for MEMS and piezoelectric actuators.

The variation limit of the effective dielectric constant increases with decreasing of product at the operating frequency of the dielectric thickness. For small values of this product, the effective dielectric constant can be varied by the relative permittivity of the dielectric material to the one unit by micromovings metal plane above the dielectric. This high controllability cannot be achieved by other methods, including the use of ferroelectrics nonlinearity.

Established criteria of maximum thickness of the dielectric, in which there is a dielectric effect, together with the catch, matching circuit by reducing the characteristic impedance in a structure with a thin layer of dielectric allows you to find a compromise between performance management and the size of the devices.

References

[1] Fedoryshyn R., Hren Y., Matiko F.: Modeling of Dynamic Characteristics of Impulse Lines of the Differential Pressure Flow Meters. *Proc. of Lviv Polytechnic National University: Heat Power Engineering. Environmental Engineering. Automation*, 659/2009, 73–78.

[2] Hu T., Desai J. P.: Soft-Tissue Material Properties under Large Deformation: Strain Rate Effect. Proceedings of the 26th Annual International Conference of the IEEE EMBS, San Francisco, 1-5 September 2004, 2758–2761.

[3] Lemberg K. V., Serzhantov A. M.: Tunable resonant microstrip phase shifter with the magnetodielectric substrate. Proceedings of International Siberian Conference on Control and Communications SffiCON. - Russia, Krasnoyarsk. – 2011, 212–214.

[4] Ortega R., Loria A., Kelly R.: A Semiglobally Stable Output Feedback PI2D Regulator for Robot Manipulators. IEEE Transactions on Automatic Control, 40/1995, 1432–1436.

[5] Poplavko Yu. M., Prokopenko Yu. V., Molchanov V.I., Dogan A.: Frequency-tunable microwave dielectric resonator. IEEE Transaction on Microwave Theory and Techniques, 48(6)/2001, 1020–1027.

[6] Prasad A.S.: Clinical and Biochemical Spectrum of Zinc Deficiency in Human Subjects. Clinical, Biochemical and Nutritional Aspects of Trace Elements, Alan R. Liss, Inc., New York, 1982.

[7] Wit E., McClure J.: Statistics for Microarrays: Design, Analysis, and Inference. 5th Edition, John Wiley & Sons Ltd., Chichester 2004.

[8] Wright and Wright, W.: Flying-Machine. US Patent No. 821393, 1906.

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