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Piezo-controlled microwave devices

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At present, millimeter wave fast tunable components are required for telecommunication systems, car collision prevention radar, etc. The only mechanical way of control inserts practically no loss in the frequency agile system. That is why micro-electromechanical systems devices are being studied intensively. In an overview, an alternative way – piezo-electromechanical tuning of microwave components – is reported.

Keywords: Tunable dielectric resonator, microwave phase shifter, piezoelectric actuator, planar transmission line, rectangular waveguide

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I. INTRODUCTION

Communication systems as well as car collision prevention radar and some military microwave electronics advance toward millimeter wavelengths. That is why new low-loss highly tunable microwave components and subsystems are necessary. The point is that currently available tunable components (microwave resonators, filters, phase shifters, etc.) use materials with controlled *intrinsic* properties, such as $\mu(H)$, $\sigma(E)$, or $\varepsilon(E)$, and have fundamental limitations in the frequency range. Their loss factor grows rapidly with frequency increase. For example, in the phase shifters, the ratio of phase change to insertion loss decreases severely with increase in frequency, particularly passing to millimeter waves.

The general physical principles of frequency agile microwave component elaboration are classified in the table of Fig. 1. Prevailing use in the decimeter and centimeter waves has components that are served by the magnetic (H-field) and electric (E-field) modes of tuning. A ferrite phase shifter in which permeability $\mu(H)$ is controlled, as well as a PIN-diode or varactor diode, where conductivity $\sigma(E)$ change is used, show frequency limitations of about 30–40 GHz. The optical way of tuning also exploits the increase in conductivity $\sigma(\Phi)$ under outside illumination by the light beam Φ, using an appropriate semiconductor component. However, similarly to the PIN-diode, a photo-PIN device inserts unacceptable loss at the millimeter waves.

A thin-film ferroelectric/paraelectric phase shifter based on the change of permittivity $\varepsilon(E)$ looks like a very promising device [1]. However, up to now, there are many technological problems that should be overcome. Dielectric losses in the ferroelectric-type components show a substantial increase approaching the millimeter wave range due to the fundamental physical reason.

Therefore, the only mechanical way of tuning inserts practically no loss in a microwave subsystem. Moreover, mechanical control is valid in any frequency range, including the millimeter wave range. In any other system of tuning, microwaves interact with the "active" material (ferrite, semiconductor, or ferroelectric) that is placed inside the microwave line, and through-passing energy is partially absorbed by this material.

In contrast, a mechanical system of control is located off the microwave propagation lines so that it makes no loss. One major disadvantage is a the minor operating speed of this technique. This overview shows that novel electromechanical facilities can rapidly satisfy customer requirements.

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II. MECHANICALLY TUNABLE COMPONENTS

A) "Macro-mechanical" tuning

One example of this method is shown in Fig. 2. By this method, the dielectric resonator (DR) can change its resonant frequency up to 3–5%. The advantage of this method is the high quality factor of the DR-based device that is preserved [2]. However, tuning is mostly quasi-static; hence displacement (Δ) usually remains fixed or can be changed occasionally.

In the same way, a mechanically tunable phase shifter, in which an inserted dielectric slab is moved toward the center of the waveguide, is applied.

In this regard, the size of the mechanical displacement of the tunable part of the device is usually large to guarantee fine tuning, and this shift, most often, is obtained manually by a screw. It is worth mentioning that the basic design of a mechanically controlled component remains of a permanent type as if it should be tuned by a screw. That is why the displacement of tunable part of the device continues to be of about the centimeter wave range (Fig. 1).

B) Tuning by a piezoelectric cantilever

The dynamic procedure of mechanical tuning is well developed; moreover, various types of movers are applied. A piezoelectric transducer in the form of a rather big cantilever is an appropriate device used for electromechanical control of $\Delta(E)$. This method creating a frequency agile DR has been patented many years ago [3] and shown in Fig. 3. The tuning range is

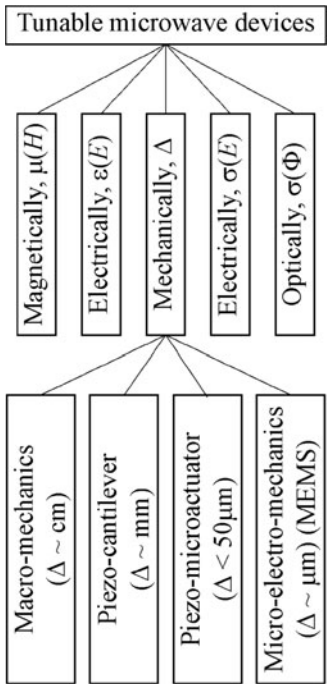

Fig. 1. Basic methods of microwave device tuning.

~6%, and common for DR in case a very high quality factor is preserved.

Recently, a similar method has been proposed to demonstrate phase shifters within the microstrip line [4] and coplanar line (CPW) [5]. Again, using a low loss "dielectric perturber", it is possible to operate up to the millimeter wave-range. Like in Fig. 3, the displacement is about 0.2–2 mm, as mentioned in the table of Fig. 1. Customary piezoelectric ceramics produce deformations of $\sim 10^{-4}$. Therefore, to provide such a big change in $\Delta(E)$, the piezoelectric controller inevitably has to be massive and, therefore, rather inertial.

Larger deformation can be achieved by the piezo-cantilever (Figs 3 and 4). However, its size is also rather big, and it cannot withstand the external vibrations that produce noise. For instance [4], to secure 1.3 mm displacement for the phase shifter, one needs a piezoelectric transducer with dimensions of $70 \times 30 \times 3\ \text{mm}^3$. Therefore, the $\Delta(E)$ control is expected to be rather slow. Indeed, the response time of this system is reported as 5 ms [5]. Using the same "perturber", coupled with a piezoelectric transducer (PET, shown in Fig. 4), many types of tunable microwave filters were studied [5]. It is obvious that the operation speed of tunable microwave components based on the piezo-cantilever is quite limited.

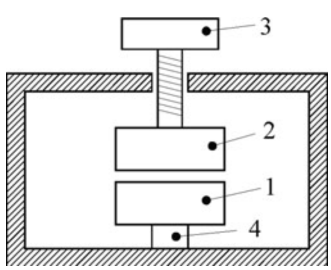

Fig. 2. Screw tunable DR: 1, 2, – two parts of the DR separated by a controlling slot; 3 – screw to adjust resonant frequency; 4 – low-ε dielectric supports.

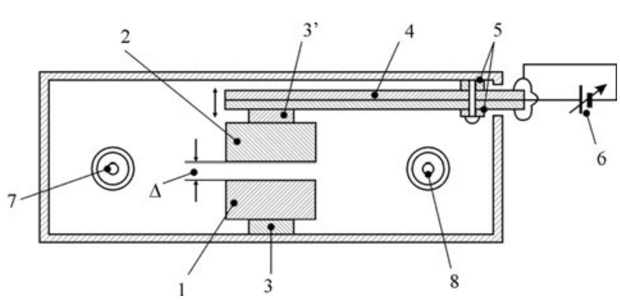

Fig. 3. Piezo-tunable DR: 1, 2 – two parts of the DR separated by a driven slot Δ 3, 3′ – low-ε dielectric supports; 4 – piezoelectric cantilever fixed at the mount; 5, 6 – voltage supply; 7, 8 – coaxial input and output [3].

C) Fast tuning by a micro-actuator

In the last few years, very fast (10^{-5} s) and miniature types of piezoelectric actuators have been elaborated [6]. These actuators can be made of electrostrictive material that has no hysteresis in the $\Delta(E)$ dependence, and can work with high accuracy (0.01 μm).

The "moonie" transducer, shown in Fig. 5 (left), consists of a piezoelectric ceramic disk sandwiched between two metallic end-caps that serve as mechanical transformers. This actuator converts and amplifies the lateral piezoelectric deformation of the disk into an axial shift normal to the plates.

The "Cymbal" actuator, shown in Fig. 5 (right), resembles the "moonie" but is more effective [7]. Conical metallic end-caps facilitate the amplification of axial displacement. At present, both types of actuators are commercial products, while their size varies from a few millimeters to centimeters. They are elaborated, in the first place, for area of hydro-acoustics. In some more recent works [8, 9], these actuators

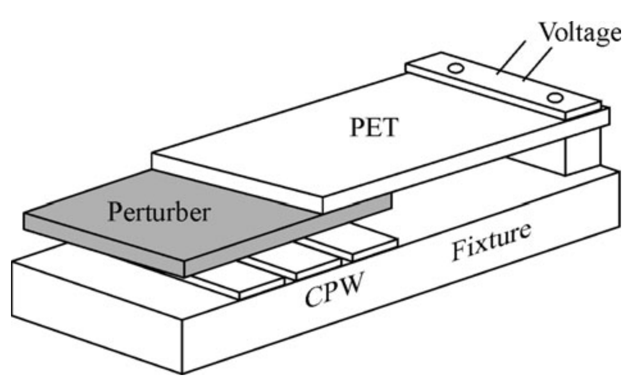

Fig. 4. Piezo-tunable CPW phase shifter [4, 5].

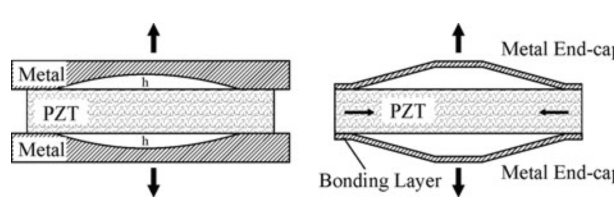

Fig. 5. Fast piezoelectric actuators: "moonie" type (left) and "cymbal" type (right) [6, 7].

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are planned for microwave tunable device implementation. The choice between these actuators depends on the design and estimated parameters of the device.

Fast actuators of the mentioned type can only provide rather small displacement, less than 100 μm. It is remarkable that the less the controlling move, the smaller and faster the actuator. Fortunately, millimeter wave devices need only 10 μm displacement for controlling. To make use of these advanced actuators at the microwave range, a new design for some tunable microwave dielectric components is discussed below.

The driving idea is to provide strong perturbation in the electromagnetic field in the area of mechanical control. For that, a discontinuity (air gap) should be embedded in the path of electric field lines perpendicular to them. The air gap is placed between dielectric plates or between a dielectric plate and an electrode. In addition, to decrease the air gap thickness, dielectrics with high dielectric constant are used.

In the following sections, based on this idea, tunable DRS, frequency agile filters, and phase shifters are described. As will be shown, these devices operate successfully with electromechanical displacements of about 40 μm.

III. HIGHLY TUNABLE DRS AND FILTERS

A DR is used in a wide variety of microwave devices, for example, to stabilize the frequency of an oscillator or as an important part of a microwave filter, being located in the shielding case or in the waveguide. DRs are made up of thermal stable ceramics with a high dielectric constant ($\varepsilon =$ 20–120) and a low loss ($\tan\delta \sim 10^{-4}$–10^{-3}). To realize a piezo-controlled phase shifter, the same ceramics should be used.

As is well known [8], electronic methods of DR resonant frequency control show a moderate tuning range ($\Delta f/f_o$) in which connection DR quality factor Q decreases greatly. For the case of optical σ-controlling, the tuning range is less than 1% while in the varactor circuit $\Delta f/f_o < 5\%$. Similarly, inserted in the DR ferrite plate provides a tuning ratio of about 3%; for integrated with DR tunable paraelectric film (with ε control), it is possible to secure $\Delta f/f_o$ around 5%.

With a high Q, DR resonant frequency f_o can be changed only by the mechanical displacement of the tuning component. However, existing designs of mechanical DR tuning, shown in Figs 2 and 3, are limited with respect to tunability and response time, because a large mechanical shift needs a rather big and thus inertial actuator.

Figure 6(b) shows another design of DR that ensures much larger tunability and high speed tuning due to stronger perturbation in the electric field while maintaining a high quality factor [8]. Realized filter designs with controlled DRs are shown in Fig. 7. Similar filters were investigated at microwave range up to 60 GHz.

Figure 6(d) demonstrates the AFC for a tunable bandpass filter made with DRs as shown in Fig. 7(a). The filter consists of two "1/2DR–slot–1/2DR" disks housed in the rectangular waveguide. One DR has an electrical dipole mode f_1 (being excited inphase with the wave in the transmission line) while another DR represents a magnetic dipole mode f_2 (providing excitation in the opposite phase). Because of this design, the modes of both resonators are independent. Hence, under the synchronous change of f_1 and f_2, the form of filter AFC is preserved in a wide spectral range. Through the pushrods, located outside the waveguide, actuators change the air slots in both resonators to control dynamically filter resonance frequency f_o.

The tuning range of the resonant frequency is about 30% while the displacement of resonator sections is about tens of micrometers. A cubic resonator, Fig. 7(b), which is a ceramics cube cut in two halves with an air slot between them, represents another type of tunable filter described in [8]. The existence of confluent modes in a cubic DR enables one to

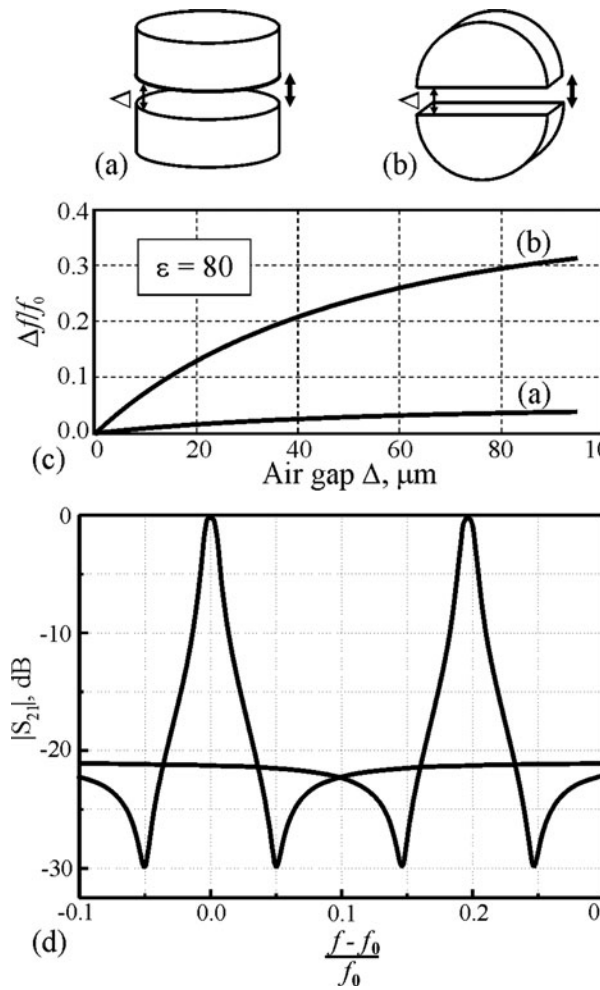

Fig. 6. DR mechanical tuning at 10 GHz: (a) ordinary manner, (b) proposed manner, (c) characteristics comparison, (d) DR and amplitude–frequency characteristic (AEC) near $f_o = 9.4$ GHz [8].

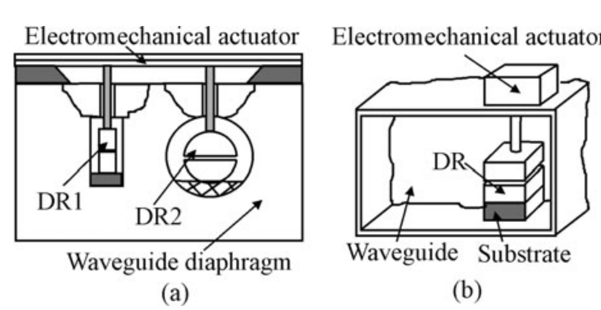

Fig. 7. Tunable DR-based filters.

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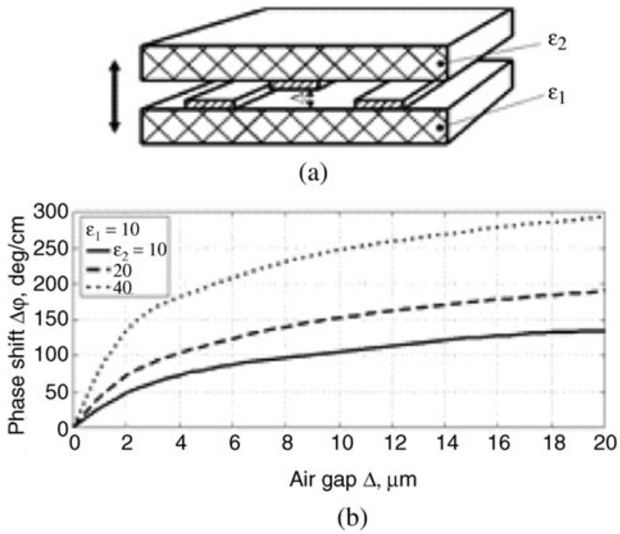

Fig. 8. CPW phase shifter. Substrate's $\varepsilon_1 = 10$ corresponding to silicon or gallium arsenide that is used in MMIC. The tunable dielectric part has $\varepsilon_2 = 10$, 20, and 40.

develop a tunable single resonator with characteristics of a multi-resonator system.

IV. PHASE SHIFTER BASED ON A PIEZO-CONTROLLED LAMINATE DIELECTRIC STRUCTURE

A new type of electrically controlled phase shifter for centimeter and millimeter waves has been recently proposed and tested in [9]. Phase control is realized by dielectric plate transposition above the CPW (Fig. 8), above themicrostrip line (Fig. 9), or inside the rectangular waveguide (Fig. 10).

To increase tunability, two methods are used: increased dielectric constant of the moveable dielectric plate and departed (detached) electrodes of the transmission line. The first method can increase tunability many times as is

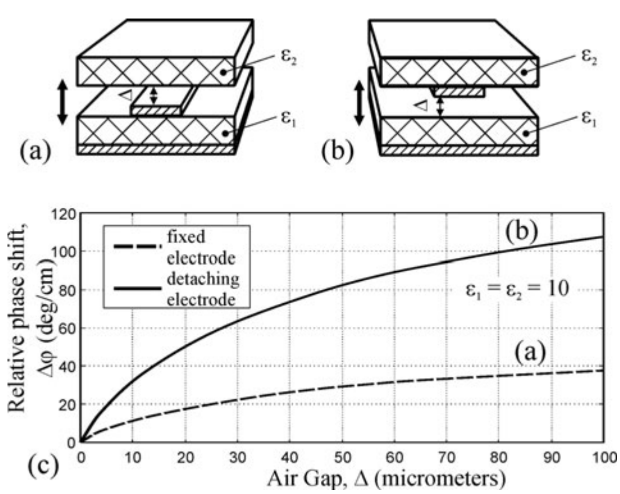

Fig. 9. Microstrip line piezo-controlled phase shifter simulation at 10 GHz: (a) known technique [2], (b) proposed way, and (c) characteristics comparison. Substrate thickness is 0.5 mm, $\varepsilon = 10$, strip width is 0.5 mm, dielectric plate thickness is 1 mm, $\varepsilon = 10$.

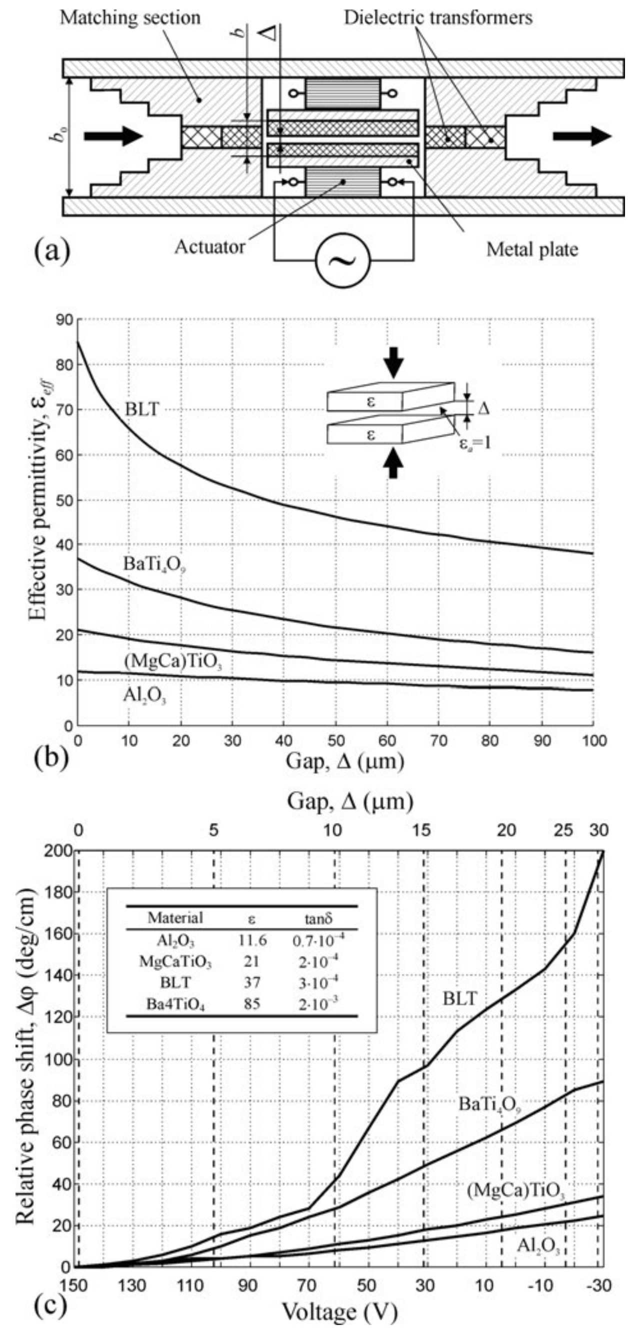

Fig. 10. Waveguide experiment with piezo-controlled phase shifter, matched at 8–12 GHz and filled by various low-loss ceramics: (a) used design, (b) effective dielectric constant versus gap size, and (c) specific (per 1 cm) phase shift depending on gap size andactuator voltage [9].

demonstrated in Fig. 8. Underway dielectric plates are made from dielectrics with increased dielectric constant: $\varepsilon_2 = 10$, 20, and 40. Correspondingly, normalized (per 1 cm length of line) phase shift increases appreciably. Tunable in this way, CPW looks like a promising device for MMIC.

The advantage of the second method is shown in Fig. 9 where two possible collocations in the electrode system for a simple microstrip line are compared under the condition that all dielectric plates have the same $\varepsilon = 10$. Evidently, the last structure provides stronger field perturbation. Earlier employed in [4], the method of phase control that is shown in Fig. 4 is about three times less effective than the new method demonstrated here. Figure 8(b) displays the simulation result.

Using both these methods, it is possible to keep within specification limits for fast controllable recent mini-actuators in order to provide analogous phase change of or more per 1 cm line length. According to actuator performance [7], the tuning response time is about 10^{-4}–10^{-5} s.

A piezo-controlled rectangular waveguide phase shifter with its characteristics is shown in Fig. 10 [9]. In a given experiment, the commercial "stack-actuator" is employed. It provides a displacement of 30 μm under a voltage of 150 V. Assuming high perfection in the metallic parts of the design, the insertion loss is caused by the loss in dielectrics. As for the inserted dielectric, used microwave ceramics have very small loss tangent (less than 10^{-3}). The figure of merit is 360° phase shift per 1 dB. At a frequency of 10 GHz and using 100 μm displacement, the change in $\varepsilon_{ef} \approx 80 - 40$ is observed for BLT ceramics; the change of $\varepsilon_{ef} \approx 35 - 20$ is registered with the $BaTi_4O_9$-type ceramics, $\varepsilon_{ef} \approx 20 - 12$ for $(MgCa)TiO_3$ ceramics, etc.

One of the greatest advantages of the studied devices is the great flexibility in design that allows the layered structure. For instance, a two fold increase in dielectric plate length results in a twofold increase in phase shift. The effective dielectric constant is not too large, which makes a matching problem using three-step Chebyshev transformers easy.

According to the purpose of the device, it is possible to choose a proper microwave dielectric, select required dimensions of the sandwiched structure, pick out the initial size of the air gap, etc. Such a design with the number of degrees of freedom makes it possible to apply the discussed air–dielectric sandwich structure (shown in Figs 8–10) as a component of various kinds of microwave devices with different properties.

As distinct from the ferrite, PIN-diode, and ferroelectric phase shifters, no fundamental frequency limitation appears over the millimeter wave range. At frequencies of 40–60 GHz and above, it is better to use, for piezoelectric tuning, microwave dielectrics with $\varepsilon = 20 - 10$. Moreover, in this case the actuator should control much less slot (of about 10 μm), so it can be faster and have less size. A low-inertia mini-actuator can be rigidly fastened inside (or butt-jointed to) a waveguide, so the device is closer to the electronic type than to the mechanical one.

V. PHASE SHIFTER BASED ON A PIEZO-TUNABLE SUBSTRATE

The principal design of this phase shifter is shown below. The gap should be designed in such a way that it provides large perturbation in an electromagnetic field. For that, piezo-controlled discontinuity (the air gap Δ) is created perpendicular to the pathway of the electric field lines. In the case of a microstrip line, the air gap may be placed between substrate and ground electrode (Fig. 11). In the same way, a "detached" signal electrode can also be moveable, being created from the metallized piezoelectric plate. The result for this kind of phase shifter investigation with three different materials of substrate is shown in Fig. 12.

To decrease the thickness of the air gap required for tuning, the substrate with larger dielectric constant should be used. Experiments and calculations also show that the phase shift is strongly dependent on design architecture. With some

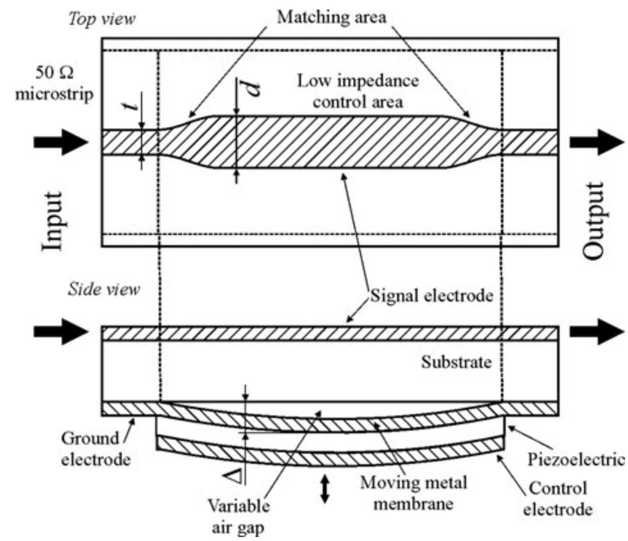

Fig. 11. Microstrip phase shifter with moveable ground electrode.

modifications, the idea of a piezo-tunable dielectric phase shifter can be applied to the RF micro-electromechanical systems (MEMS) devices using piezo-driven MEMS design. The piezoelectric method to force micro-bridge movement looks very promising.

A phase shifter based on a coplanar waveguide deposited onto quartz or another substrate is shown in Fig. 13. At both sides of the CPW golden anchors are placed, which are supported by a nitride-film bridge 1. This film plays the role of a dielectric perturber of CPW with $\varepsilon \sim 7$ and acts as a spring as well. On the top of nitride film platinum electrode 2 should be deposited. It is electrically connected to one of the anchors. Another electrode 4 is connected to the second anchor. These two bias the piezoelectric film 3 sandwiched between them. Under applied voltage, the piezoelectric film bends up and down moving all attached parts. To avoid air damping, many holes should be etched along the bridge (they are not shown in Fig. 13). If only metallic layers move one to another in the air slot, the impedance of the line will severely decrease while no phase shift might be observed, Fig. 14, curve 2 (only the capacitance between electrodes will be changed, and that is the mode of operation of RF MEMS with electrostatic control). However, phase shifter proposed here is a *dielectric* one, so due to the moveable dielectric plate (shown in Fig. 14) the piezo-tunable movement produced needs phaseshift, Fig. 14, curve 1.

In the common MEMS device, electrostatic interaction is used between the signal electrode and the metallic bridge. However, as is obvious (and confirmed by calculation), the

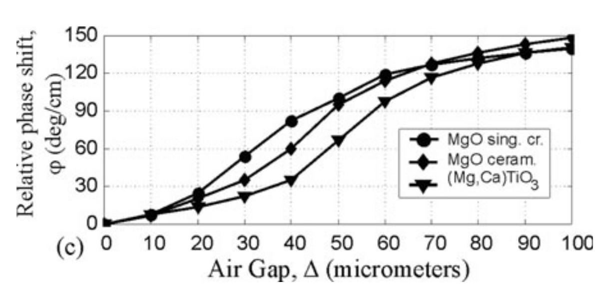

Fig. 12. Phase shift versus gap experimental dependence, substrate $\varepsilon \sim 10 - 20$.

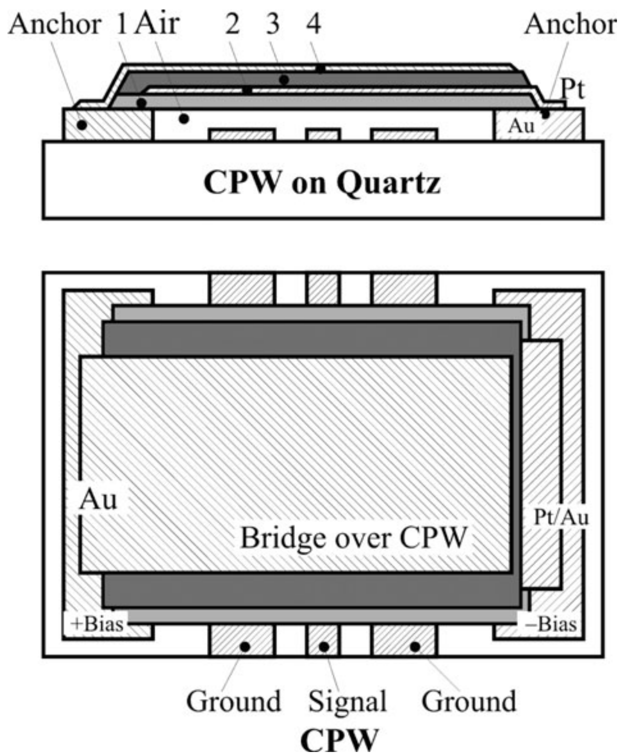

Fig. 13. Scheme of piezo-controlled CPW phase shifter.

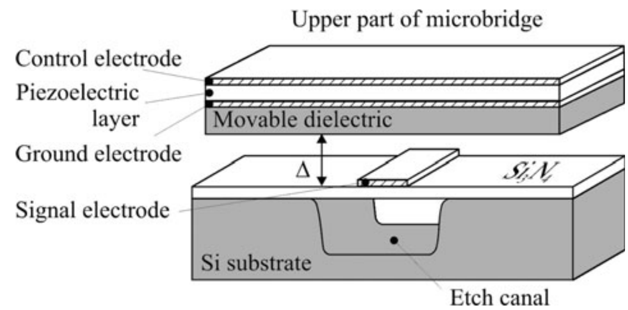

Fig. 15. Suspended microstrip line under piezo-moveable bridge.

approach of electrodes itself cannot change the phase but greatly decreases line impedance. Hence, a common MEMS phase shifter is realized as the ensemble of many inserted tunable micro-capacitors that results in a large number of resonances in the system [10].

Similarly, a millimeter wave phase shifter might be designed by MEMS technology with suspended microstrip line on silicon substrate, Fig. 15. A signal electrode is allocated on the thin Si_3N_4 membrane, so that the air surroundings decrease insertion loss. The new idea is not only to apply a piezo-actuator but also to use moveable "dielectric" (Fig. 15) in the piezo-driven MEMS phase shifter. A really moveable "dielectric" might be high resistive silicon ($\varepsilon \sim 12$) or another dielectric that is consistent with "grown-up" technology. Specific phase shift is shown in Fig. 16. The key role of moveable dielectric is obvious: without it phase shift is practically absent because $\varepsilon \sim 1$.

VI. TUNABLE MICROSTRIP FILTER BASED ON A PIEZO-TUNABLE SUBSTRATE

The proposed technique of tuning is used to transform any microstrip filter into a frequency agile device. Thus, the substrate, located under a microstrip device, becomes a "tunable dielectric". Namely, part of the ground electrode (just under the filter) is removed and substituted by the closely adjoining substrate metallic plate, Fig. 17a. This plate is a ground electrode of the piezo-actuator. The thickness of the narrow air gap (Δ) is electrically controlled. At microwaves the range of change is from $\Delta \sim 10$ μm till $\Delta \sim 100$ μm, while at millimeter waves the range of $\Delta \approx 3 - 10$ μm is usually sufficient.

Such a "tunable substrate" is described as a dielectric in which effective permittivity is controlled. The range of ε_{eff} change depends on substrate and on the relationship Δ/h, where h is substrate thickness. The example of $\varepsilon_{eff}(\Delta)$ dependence is shown in Fig. 17(b) for alumina substrate (usually utilized at centimeter waves). Usable at millimeter waves, quartz substrate shows tunability $\varepsilon_{eff} \approx 4 - 2$. In both cases, practically no loss is introduced in the device under the proposed type of tuning.

Experimental confirmation of the new method of tuning is made with a simple regular $\lambda/2$ microstrip resonator, Fig. 18(a). For the chosen case, substrate with high permittivity is served ($\varepsilon = 35$). Higher ε allows considerable decrease in tunable gap thickness, which in turn makes it possible to apply a smaller and faster actuator. Frequency response dependence for two utmost positions of the ground electrode is shown in Fig. 18(a). Resonant frequency change is about 15%. Characteristics of the double-resonator filter realized on commercial alumina substrate are shown in Fig. 18(b).

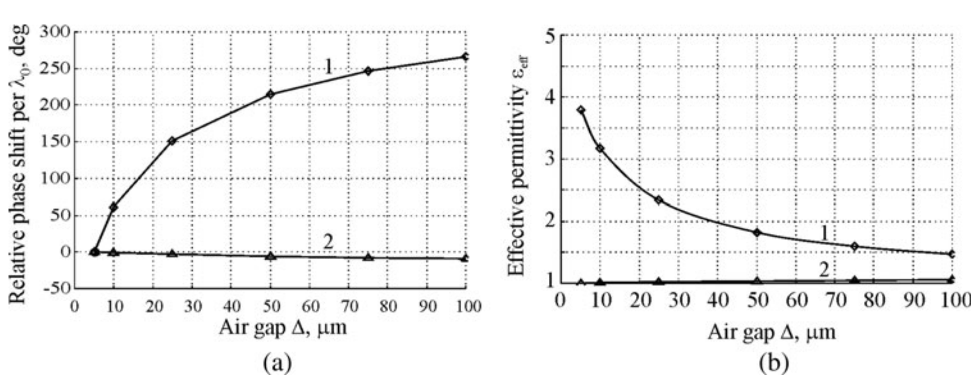

Fig. 14. Calculated phase shift per 1 cm and effective dielectric constant of the system in Fig. 13: 1 – with moveable dielectric; 2 – without moveable dielectric.

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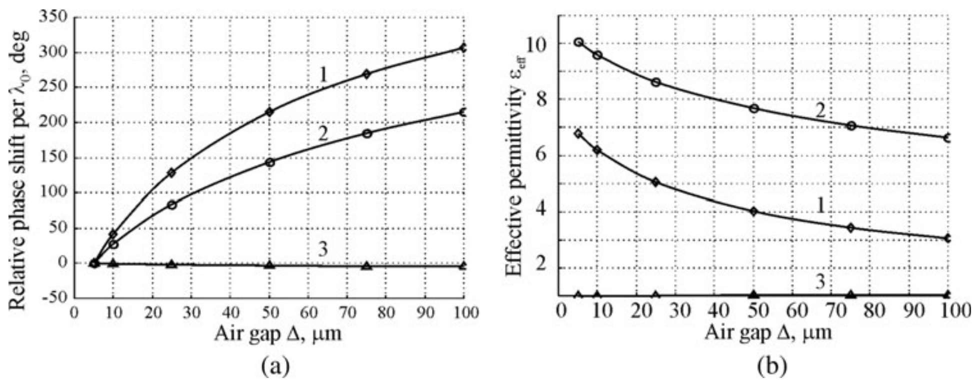

Fig. 16. Calculated phase shift per 1 cm and effective dielectric constant of the system: 1 – as shown in Fig. 15; 2 – without etched canal; 3 – without moveable dielectric.

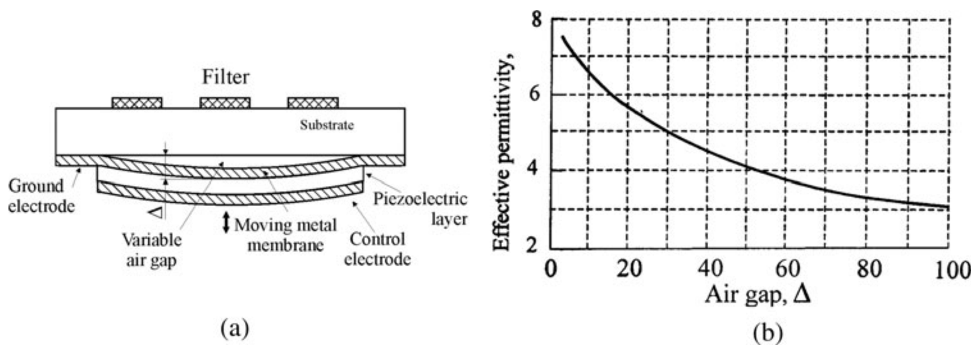

Fig. 17. Principle of substrate effective dielectric constant tuning: (a) – side view of moving ground electrode under the substrate and, (b) – calculated ε_{eff} – change in the case of $\varepsilon_D = 10$ for an alumina substrate thickness of 0.65 mm.

Filter tunability is ~10%, and it is seen that no additional loss is inserted.

VII. DISCUSSION

Low-loss highly tunable microwave material can be fabricated using dielectric laminate structure in which effective dielectric constant ε_{eff} is efficiently controlled. The proposed combined structure usually consists of two dielectric parts with an air gap between them. This gap has to be arranged in such a way that it provides the largest perturbation in the electromagnetic filled. By means of a fast piezoelectric mini-actuator, the size of the air gap is changed. As a result, ε_{eff} of the given structure strongly varies, which is used for device control. Wide-band low-loss waveguide phase shifters, highly tunable DRs, and, based on them, 20% tunable filters are realized experimentally.

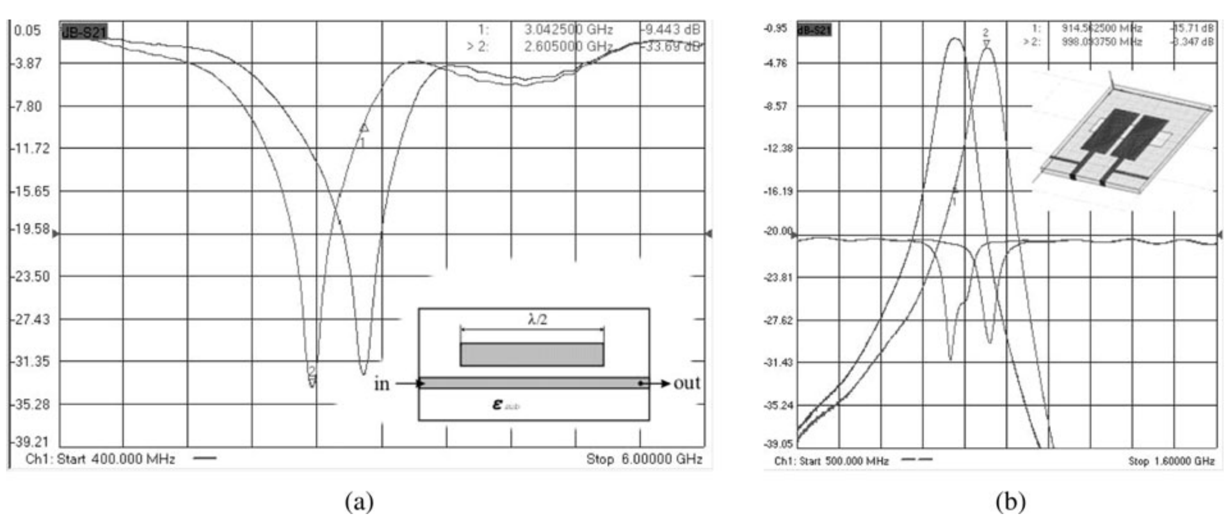

Fig. 18. Microstrip resonators: (a) – first mode of $\lambda/2$ in a stop band mode regime; resonator width is 1.6 mm, its length is 6.8 mm, gap is $\Delta = 40$ μm, frequency change is $\Delta f = 0.44$ GHz and; (b) – tunable double-resonator filter characterization.

New modifications of the piezoelectric method of microwave filters frequency control as well as the possibility of creating phase shifters at microwaves/millimeter waves are discussed. Phase control is realized by dielectric plate transposition inside the rectangular waveguide or above the CPW. Due to a peculiar collocation of electrodes with the high-ε dielectrics adaptation, a very small mutual displacement of dielectric plates is enough to obtain the large phase shift. The devices have minor insertion loss because high-quality dielectric materials are used. The effect of effective-ε controlling by air slot change is especially pronounced in DR frequency tuning.

With examples of waveguide, microstrip and coplanar phase shifters, and waveguide and microstrip tunable filters, it is shown that electromagnetic field strong perturbation by small mechanical displacement provides a method of fast and efficient control.

VIII. CONCLUSION

The aim of this paper is to describe microwave devices with low cost, high operating speed, high frequency (tested up to 40 GHz), and high quality factor based on the piezoelectric tuned dielectric-based devices. The mechanism of piezoelectric control is discussed as ε_{eff} change in the active part of the dielectric device. It is supposed that an effective way of tuning is to use the "microwave dielectric – air gap", controlled by the fast electromechanical actuator. In addition, a minimal loss is inserted in the tunable component. Using high-quality microwave dielectrics, it is possible to realize low-loss filters and phase shifters not only in microwaves but also in millimeter waves. The proposed structures are studied in microstrip and coplanar designs.

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