Low Loss Phase Shifter Based on Piezo-Controlled Layered Dielectric Structure

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Abstract **— Layered structure made of high-ε dielectric and piezo-controlled air slot, filling various type waveguides, is used as tunable low loss wide-band phase shifter. Contemporary piezoelectric actuator is employed for fast variation of air slot width. This alteration results in considerable change in effective dielectric constant ε_{ef} of the structure. Using high quality microwave dielectrics, it is possible to realize low loss phase shifters in the microwaves as well as in the millimeter waves.**

Index terms**: phase shifter, piezoelectric control, low loss microwave dielectric**

I. INTRODUCTION

PHASE shifters of compact size, low cost, and high-speed operation in centimeter and millimeter waves are required for telecommunication systems, car collision prevention radar, etc. Cardinal limiting property of currently available tunable microwave components is their loss factor that raises with the frequency. Common phase shifters, where one of intrinsic property $\mu(H)$, $\sigma(E)$ or $\varepsilon(E)$ of material is electronically controlled, have a principal limitation in the usable frequency range. The figures of merit of those phase shifters (the ratio of phase-shift to insertion-loss) decreases rapidly with frequency increase, particularly, approaching the millimeter waves.

Ferrite phase shifter that based on $\mu(H)$ change as well as PIN or varactor diodes with $\sigma(E)$ control have frequency limitation of about 30-40 GHz [1]. Ferroelectric (paraelectric) thin film phase shifters with the change in $\varepsilon(E)$ still have technological problems that have to be overcame [2]. Surface acoustic wave devices are limited to frequency below 5 GHz [3]. Recently invented thin film bulk acoustic wave resonators are also reported to be operational only up to 10 GHz [4]. Thus, at the millimeter waves, where car collision radar has allowed frequency range, and "local area" telecommunications are expanded, all mentioned devices have insufficient performance.

It seems that the only mechanical control introduces practically no loss in a system, and, moreover, mechanical control is feasible in any frequency range, including millimeter wave range. Mechanical tuning of microwave components has been long known: metallic or dielectric component part has to be shifted inside waveguide or resonant cavity. Such a mechanical tuning is mostly quasi-static, so it is usually remain fixed or can be changed only occasionally. In addition, the mechanical shift (Δ) of tunable part is usually large to guarantee a fine tuning, and often achieved manually by screw [5].

Dynamic mechanical tuning has been introduced recently, utilizing piezoelectric transducer for electromechanical control, $\Delta(E)$ [5]. Nevertheless, the basic design of mechanic controlled component keeps such a big shift (Δ is about several millimeters) as if it should be tuned by screw. In this reason, to provide such a big change in $\Delta(E)$, the piezoelectric controller inevitably has to be a massive device, and, therefore, inertial.

Recently a very fast (10^{-5} s) and miniature piezoelectric actuators are elaborated [6], and proved to be employable in the microwave range [7]-[9]. Electrostrictive ceramics actuators show no hysteresis in the $\Delta(E)$ dependence, and have high accuracy (0.01 μm).However, those actuators can provide a comparatively small displacement (less then 100 μm).

In this study, a new type phase shifter is designed to realize very loss as in microwaves so in millimeter waves. Similarly to ferroelectric phase shifter, the new device is based on the principle of dielectric permittivity $\varepsilon(E)$ control, however, effective dielectric permittivity ε_{ef} is under control rather than materials intrinsic permittivity. Therefore, instead of very big ε inherent in ferroelectric new device deals with much lower ε_{ef} that facilitates matching problem. The ε_{ef} of proposed phase shifter is controlled by comparatively low voltage in contrast to ferroelectric devices. Low loss microwave dielectrics are used in our layered tunable structure, so proposed device is characterized by small insertion loss up to the millimeter waves.

It should be noted that the manner of microwave device control proposed in this work was used previously to control resonant frequency of dielectric resonator [7]. There are also some resembling ways of electromechanical control by phase shifters [5], [11]. However, their manner of phase control is different from the proposed here. In our case, due to especial collocation of electrodes and high-ε dielectric utilization, a very small mutual displacement of dielectric plates is enough to obtain large phase shift., so fast actuator can be used for fast control.

II. WAVEGUIDE PIEZO-CONTROLLED PHASE SHIFTER

To illustrate the efficiency of new type phase shifter, a simplified design with tunable structure "dielectric – air slot" is realized in common X-band rectangular waveguide.

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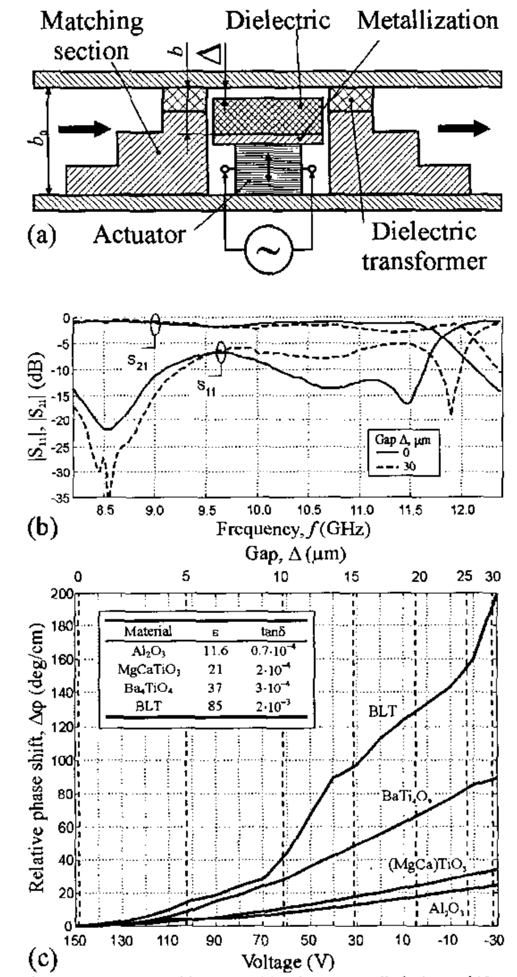
Basic diagram of this phase shifter is shown in Fig. 1(a). The cross section of the waveguide is partially filled by moving dielectric plate of 1-2 mm in thickness and 10 mm in length. Made from the low loss materials with $\varepsilon = 12 - 80$, plate is connected to actuator. At the maximum of actuator enlargement, the dielectric plate is placed in touch with the waveguide wall. Next the controlling voltage is decreased, that made a gap appear, and effective dielectric constant of the air-dielectric composite decreases, resulting in differential phase shift. Actuator itself is eliminated from electromagnetic field of travelling wave.

In a given experiment, commercial "stackactuator" is employed. It provides displacement of 30 micrometers under the voltage of 150 V. Its own resonant frequency is about $f_R = 30$ kHz, that limits the response time. At present, faster actuators with the $f_R \geq 150$ kHz are available [6].

Three-step Chebyshev transformers realize wide-band matching of the device. Even though perfect matching was



Material	ε	tanδ
Al_2O_3	11.6	$0.7 \cdot 10^{-4}$
$MgCaTiO_3$	21	$2 \cdot 10^{-4}$
Ba_4TiO_4	37	$3 \cdot 10^{-4}$
BLT	85	$2 \cdot 10^{-3}$

Fig. 1. Experiment with waveguide piezo-controlled phase shifter, matched at 8–12 GHz and filled with various low loss ceramics: (a) schematic of longitudinal section view of the device with an actuator attached to dielectric tuning plate; (b) measured amplitude-frequency characteristics; (c) observed specific (per 1 cm) phase shift depending on gap size and actuator voltage.

not the primary object of this experiment, the return loss is about -10 dB, as shown in Fig. 1(b).

The change in the phase φ with controlled air gap Δ by voltage applied to actuator is presented in Fig. 1(c) for various dielectrics employed. Differential phase is normalized per 1 cm length of moving plate. Depending on moving plate dielectric constant, relative phase shift of 25 - 200 deg/cm was achieved.

An important characteristic of microwave device is its insertion loss. The loss inserted by dielectric plate itself is calculated as 0.1 - 0.001 dB/cm because used microwave ceramics have very small loss ($\tan\delta = 10^{-3} - 10^{-4}$). In studied device, the loss is caused mostly by the design imperfection, and was less than 1 dB.

Besides low loss and wide-band, the advantage of proposed device is a great flexibility of proposed layered structure design. For instance, two times increase in the length of dielectric plate results in twofold increase in the phase shift. According to the purpose of device, it is possible to choose proper microwave dielectric, to select need dimensions of sandwich structure dimensions, to pick out initial size of air gap, to sort out the actuator, etc.

Such a design with the number degrees of freedom makes it available to apply the air-dielectric sandwich structure as a component of various kinds of microwave devices with different properties.

III. Layered Dielectric Phase Shifter Simulations

Dielectric constant is a critical parameter to determine signal propagation constant. As microwave propagation constant β changes by external electric control E, the wave passes through the waveguide with controllable phase shift $\varphi(E)$. In this work, the phase shifter is realized by means of mechanically tunable dielectric layered system. Its effective dielectric constant ε_{ef} is efficiently controlled by means of piezoelectric mini-actuator that changes a gap Δ between two dielectric plates: $\Delta(E)$.

Fig. 2 shows the change in effective dielectric constant ε_{ef} with the gap width Δ in the rectangular waveguide. Two equal dielectric plates of 1mm thickness have dielectric constant correspondent to the experiment described in Fig. 1. The change $\varepsilon_{ef} \approx 80 - 40$ is observed for BLT ceramics; the change $\varepsilon_{ef} \approx 35 - 20$ is registered with the $BaTi_4O_9$ type ceramics, and $\varepsilon_{ef} \approx 20 - 12$ for $(MgCa)TiO_3$ ceramics, etc. This order of magnitude of dielectric constant facilitates matching problem in comparison with ferroelectric phase shifter.

Piezo-controlled layered dielectric phase shifter has particular interest for microstrip and coplanar lines. These quasi-TEM mode lines have no cutoff frequency, and are wide-band in their nature. To increase operation speed of device and decrease its size, a small mechanical shift should produce big effect.

The idea is to provide a very strong perturbation in the electromagnetic field by a small displacement. The task is realized by introducing discontinuity on the way of electric field in a form of varying air gap between dielectric plates.

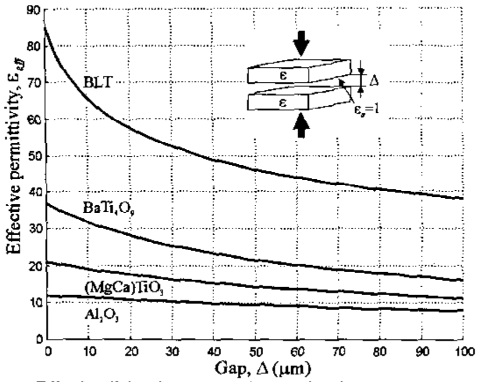


Fig. 2. Effective dielectric constant of two dielectric plates in waveguide with air gap Δ.

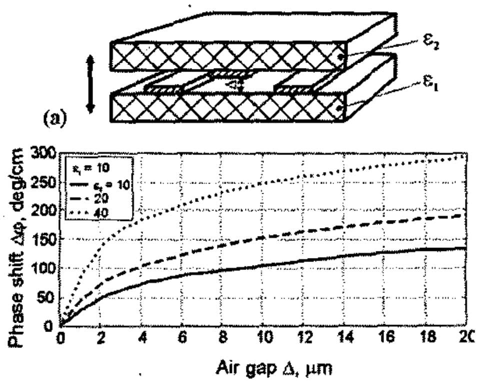


Fig. 4. Schematics and simulation of coplanar line phase shifter at 10 GHz. Subtrate's ε = 10.

To increase tunability, two methods are used: detached (departed) electrodes, and increased dielectric constant.

The advantage of the first way is demonstrated in Fig. 3 where two possible collocations in the electrode system in the microstrip line are compared under the condition that both dielectric plates have the same ε = 10. Fig. 3(a) demonstrates traditional microstrip line tunable by the dielectric plate-perturber moving over the line [8]. New approach shown in Fig. 3(b) is distinguished by that the ground electrode and the center electrode are deposited onto different dielectric plates that have a controllable air slot between them. As a result, the microwave electric field lines should obviously cross the air slot, which ε =1 is much less than the ε = 10 specific for moving dielectric plate. Evidently, the last structure provides more strong field perturbation. Earlier employed in [8] method of phase control, shown in Fig. 3(a), is about 3 times less effective than proposed in Fig. 3(b) new method. Fig. 3(c) displays the result of simulation.

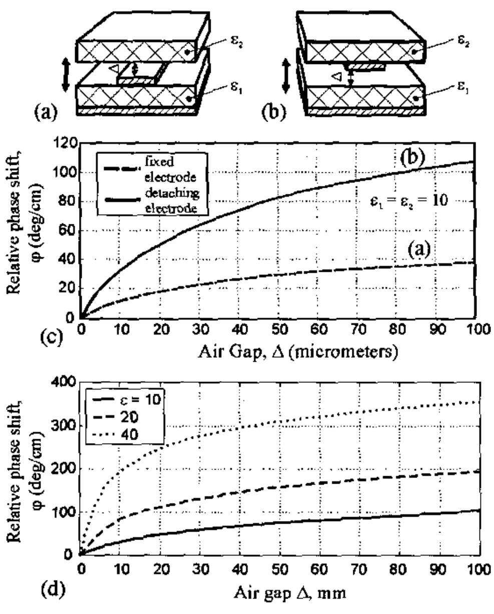


Fig. 3. Piezo-controlled microstrip line phase shifter simulation: f=10 GHz, substrate thickness is 0.5 mm, ε = 10; strip width is 0.5 mm; moving dielectric plate (thick = 1mm) has the same ε = 10: (a) microstrim is fixed on substrate [8]; (b) new design with the strip attache to the upper moving dielectric plate; (c) comparison of phase shift for two cases in (a) and (b); (d) phase shift in design (b) with various ε of moving dielectric plate.

Second way to increase tunability in many times is demonstrated in Fig. 3(d). One of dielectric plates has an increased ε. For simulation, we choose transmission lines that consist of two dielectric plates: substrate with lower permittivity (ε = 10), and moving plate with ε = 10, 20, 40. Calculation shows that microstrip line at the frequency of 10 GHz, using higher-ε moving plate, can provide phase shift of $\varphi \approx 2\pi$ per centimeter of line length, Fig. 3(d).

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

Tunable coplanar line characteristics shown in Fig. 4 appear very promising for MMIC device. The effect of phase would be much stronger if the substrate is made with lower-ε dielectric (ε = 2 – 4). However, substrate parameter ε = 10 is chosen here because of silicon and gallium arsenide are usually used in the MMIC. In the frequency range of 40-60 GHz the size of dielectric plate integrated with actuator is estimated as 5×2×2 mm^3. This allows decrease response time of such tunable devices.

IV. EXPERIMENT WITH MICROSTRIP LINE PHASE SHIFTER

Using microstrip lines and network analyzer, various modes of mechanical phase shift is experimentally studied. As it is expected from simulations, the increase in ε of the moving plate gives rise to specific phase shift φ: Fig. 5(a), where MgO single crystal has ε_{sc}=10, MgO ceramics has ε_{cer}=8, others are listed in Fig. 1. In the same way, specific φ rises essentially with increase in ε-discrepancy between the substrate and moving plate, Fig. 5(b). However, the largest steepness of tuning characteristic curve is obtained for the case of detached electrodes, Fig. 5(c). As a whole, experiments justify proposed ideas how to increase phase

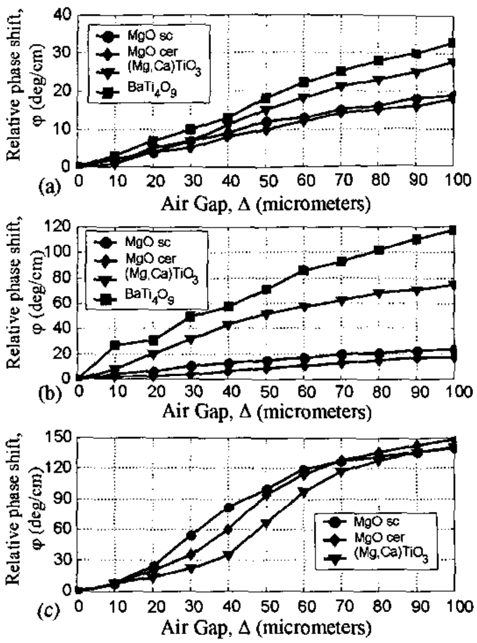


Fig. 5. Microstrip line piezo-controlled phase shifter measured at 5 GHz: (a) fixed electrode design shown in Fig. 3a, substrate $\varepsilon = 10$; (b) the same but substrate $\varepsilon = 2.03$; (c) detached electrode as in Fig. 3 (c), substrate $\varepsilon = 10$.

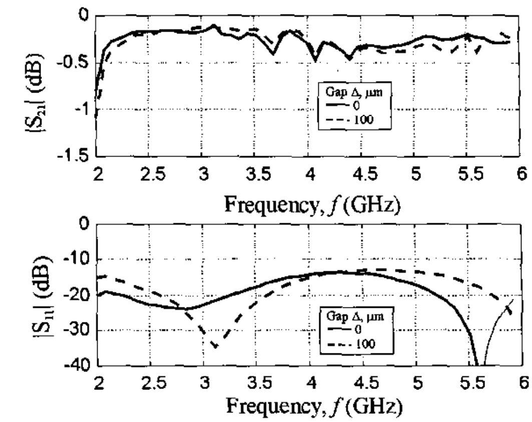


Fig. 6. Measured amplitude-frequency characteristics of the device with detached electrode, as in Fig, 3b and in Fig. 5c.

shift by electromechanical manner in order to answer fast actuator capacity. This method of phase control inserts practically no loss, Fig. 6.

V. Conclusion

Piezoelectric controlled wide-band phase shifter for microwaves and millimeter waves is proposed and tested at microwaves. Dielectric plate, moving inside or nearby a waveguide, realizes the control of phase. Using higher-ε dielectrics, it is possible to decrease essentially need displacement; therefore, to use recent fast (10^{-5} s) mini-actuators.

As distinct from the ferrite, PIN diode and ferroelectric phase shifters, no frequency limitation appears going over millimeter waves for proposed piezoelectric controlled phase shifter. Moreover, above the frequencies of 30 - 40 GHz, it is better to use dielectrics with $\varepsilon = 20 - 10$, while the actuator should control much less slot of about 10 μm, so it can be more fast and has less size. As against to others piezoelectric controlled microwave devices, a low inertia mini-actuator can be rigidly fasten inside or butt-jointed to waveguide, so the device is much more closer to the electronic type rather than to mechanical one.

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