Piezo-controlled Dielectric Phase Shifter

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Abstract

A sandwich structure of dielectric material and air gap inside a rectangular waveguide is proposed as a fast electrically tunable low-loss phase shifter. As the dielectric material is shifted up and down by piezoelectric actuator and, thereby, the thickness of air gap is changed, the effective dielectric constant of the sandwich structure is varied. Phase shifters based on the sandwich structure with different dielectric materials showed phase shift of 20~200 °/cm at X-band as the thickness of air gap varied up to 30 μm. The idea can be extended toward low-loss millimeter wave phase shifters since modern microwave ceramics have been developed to show very low dielectric loss(tan $\delta \sim 10^{-4}$).

Key words : Phase Shifter, Piezoelectric Actuator, Microwave Dielectric, Rectangular Waveguide.

I. Introduction

Tunable phase shifter is one of the essential components in modern microwave systems. The performance of phase shifters such as the ratio of phase shift to insertion loss and the operation speed depends heavily on the frequency. The attenuation of available phase shifters rises severely as the operation frequency increases[1]~[3]. Growing interest on modern communication and radar systems, however, expects a steady growing in their operation frequencies. Moreover, frequency resources in the microwave region are near exhaustion. Thus new types of phase shifter which could operate with an acceptable loss at the millimeter wave range are under serious examination[4]~[6].

One interesting application of the phase shifter is the phased array antenna, which provides fast steering of electromagnetic beam[7]. Conventional phased array antenna adopts mostly the phase shifter made of ferrite, of which magnetic susceptibility, μ, is controlled by the bias of magnetic field, H_b[8]. Ferrite phase shifter, however, requires large and complex structures and high power to apply required magnetic field[9]. Moreover, there exists the frequency limitation up to around 30 GHz[10]. The PIN diode based phase shifter, where the conductivity, σ, is controlled by the applied electric field, E, is advantageous for its small size and high speed[8]. However, diode phase shifter usually suffers from high insertion loss[9], and its frequency limitation is up to also around 30 GHz. The phase shifter based on MEMS uses electronic control over the conductivity, which inevitably means increased losses[11]. Recently, ferroelectric phase shifter has been widely investigated both in the form of bulk[9] and thin film[12]. As a bias of electric field, E_b, is applied to the ferroelectric material, its dielectric constant(ε) is changed. However, ferroelectric phase shifters in the bulk form need extremely high bias voltage, whereas, those in thin film form suffer from large dielectric loss. Because the phase shifters mentioned so far control the intrinsic characteristics of materials such as $\mu(H)$, $\sigma(E)$, or $\varepsilon(E)$ to induce the phase shift, they tend to suffer from fundamental frequency limitations and high losses as the operation frequency increases.

Phase shifter using piezoelectric control over the microstrip line was reported recently[4],[13]. The device showed low loss but utilized long cantilever to perturb microwave signals on the microstrip line. Similar idea was used for phased-array antenna system[14]. In both cases piezoelectric cantilever should provide big displacement(of a few millimeters), which inevitably makes the device massive, slow and sensitive to external influences due to mechanical vibration.

Recently a fast(10^{-5} s) and miniature-type piezoelectric actuator was used for dielectric resonator tuning[15]. Moreover, the actuators made of electrostrictive materials show no hysteresis, and work with relatively small displacement, usually less than 100 μm, but with high accuracy(about 0.01 μm). Therefore, microwave tunable devices made of such electrostrictive materials are much smaller and faster in response.

Utilizing such advanced actuators, a new design of tunable microwave dielectric phase shifter is proposed here.

Manuscript received July 26, 2005 ; revised February 17, 2006. (ID No. 20050726-027J)
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The driving idea is to apply a strong perturbation in the electromagnetic field by the electromechanical control. A discontinuity is embedded on the path of electric field lines in a form of varying air gap between dielectrics and waveguide wall. In addition, to limit the air gap thickness and to shorten response time, dielectrics with relatively high dielectric constants are adopted.

The new type of phase shifter is based on a layered structure using high dielectric constant material and small air gap inside a rectangular waveguide[15], although the idea can be applied for other types of transmission lines. As the dielectric material is shifted up and down inside a waveguide and, thereby, the thickness of air gap is controlled, the effective dielectric constant of the sandwiched structure can be controlled. Fast movement of dielectric plate to control the narrow air gap inside a waveguide was realized by piezoelectric actuator. Phase shifter with the layered structure does not utilize variation of the intrinsic characteristics of materials but relies on the change in effective parameters under electromechanical reconfiguration, namely variation of air gap thickness, while intrinsic parameters of high quality microwave dielectrics remain stable. Thus, proposed phase shifter has no fundamental limitation due to dielectric loss by increasing operation frequency.

II. Electromagnetic Field Analysis of Dielectrics - Air Gap Composite

A basic model shown in Fig. 1 is used to evaluate quantitatively the influence of air gap between a dielectrics and waveguide wall on wave propagation properties. For a partially filled waveguide, instead of pure TE or TM mode their hybrid modes, LSM(Longitudinal Section Magnetic) mode in this case, begin to dominate[16]. The solutions of Maxwell equations for x- and z-components of electric (E) and magnetic (H) field in each uniformly filled section 1 and 2 of the waveguide can be presented in the form:

$$\mathbf{E}_{x1(2)}=\frac{\beta_x\beta_y}{\beta_x^2+\gamma^2}Ae^{-j\gamma z}\sin(\beta_x x-\phi_x)\sin(\beta_{y1(2)}y-\phi_{y1(2)});$$

$$\mathbf{E}_{z1(2)}=\frac{j\beta_y\gamma}{\beta_x^2+\gamma^2}Ae^{-j\gamma z}\cos(\beta_x x-\phi_x)\sin(\beta_{y1(2)}y-\phi_{y1(2)});$$

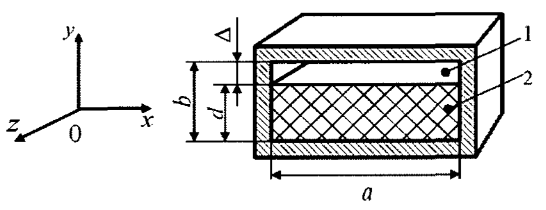


Fig. 1. Waveguide partially filled by a dielectric slab.

$$\mathbf{H}_{x1(2)}=-\frac{\gamma\omega\,\dot{\varepsilon}_{1(2)}\varepsilon_0}{\beta_x^2+\gamma^2}Ae^{-j\gamma z}\cos(\beta_x x-\phi_x)\cos(\beta_{y1(2)}y-\phi_{y1(2)});$$

$$\mathbf{H}_{z1(2)}=-\frac{j\beta_x\omega\,\dot{\varepsilon}_{1(2)}\varepsilon_0}{\beta_x^2+\gamma^2}Ae^{-j\gamma z}\sin(\beta_x x-\phi_x)\cos(\beta_{y1(2)}y-\phi_{y1(2)}) \qquad (1)$$

where A is an amplitude of electromagnetic field, ε_0 is the dielectric constant of vacuum, $\dot{\varepsilon}_{1(2)}=\varepsilon_{1(2)}(1-j\tan\delta_{1(2)})$ represents complex relative permittivity of each medium, □ is a propagation constant, β_x and $\beta_{y1(2)}$ are transverse wave numbers in each uniform part of the waveguide, ϕ_x and $\phi_{y1(2)}$ are transverse phases of electromagnetic field distribution while ω is the circular frequency.

Boundary conditions and continuity requirements for tangential components of electromagnetic field at the air-dielectric boundary give a nonlinear equation for the low-order mode:

$$\beta_{y1}\tan(\beta_{y1}\Delta)+\frac{\beta_{y2}}{\dot{\varepsilon}}\tan(\beta_{y2}(b-\Delta))=0 \qquad (2)$$

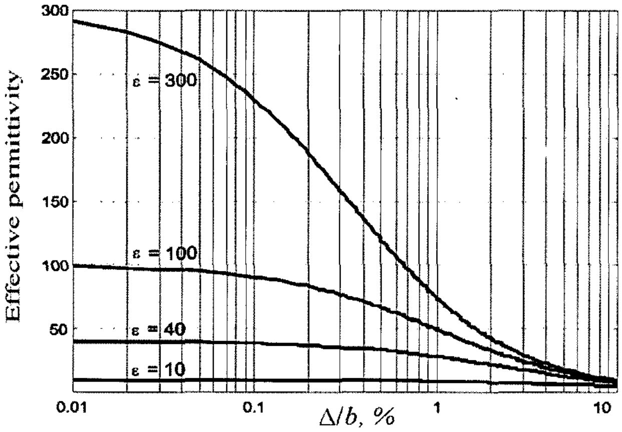
where $\beta_{y1}=\sqrt{k^2-\gamma^2-\beta_x^2}$ is the transverse wave number in the air gap region, $\beta_{y2}=\sqrt{\dot{\varepsilon}k^2-\gamma^2-\beta_x^2}$ is transverse wave number in the dielectric region, $\dot{\varepsilon}$ is complex permittivity of the dielectrics, k is the wave number in free space, b is the thickness of air-dielectric sandwich, and □ is the thickness of air gap between the dielectrics and waveguide wall. This equation is solved numerically to obtain the complex propagation constant and then directly measurable characteristics.

It is convenient to characterize wave propagation conditions with the effective permittivity, ε_{eff} of partially filled waveguide. This parameter is equivalent to the permittivity of fully loaded waveguide that gives the same propagation constant as the partially filled waveguide. For the basic mode of rectangular waveguide the effective permittivity can be expressed as:

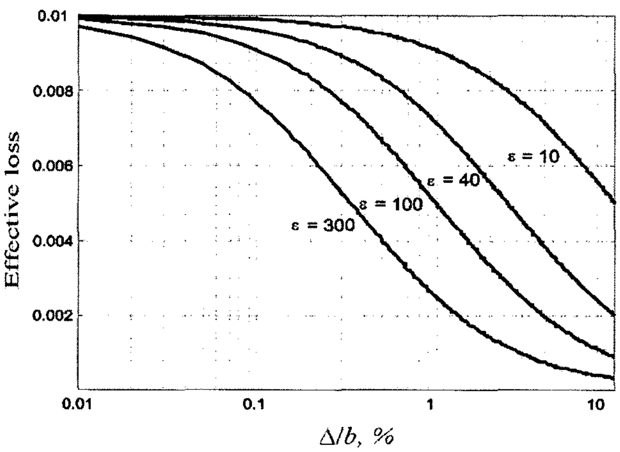
$$\varepsilon_{eff}=\frac{(\pi/a)^2+\gamma^2}{k^2} \qquad (3)$$

where γ is the propagation constant, k is the wave number in free space, and a is the width of waveguide. Simulation results are presented in Fig. 2 showing the effective permittivity and effective loss as a function of air gap and dielectric constants of dielectric slab. Strong influence of the air gap thickness is evident particularly for high-ε materials. For instance, introduction of 10 μm air gap which is equivalent to 0.1 % of the height of standard X-band waveguide filled with the dielectrics of ε=100, and tan δ=0.01 reduces the effective permittivity and loss by almost 10 %.

III. Phase Shifter Design and Simulation



(a) Effective permittivity



(b) Effective loss

Fig. 2. Effective parameters of partially filled waveguide: Δ is the air gap, b is the waveguide height.

A simple device was designed and constructed to realize phase shift with the air-dielectric sandwich structure as shown in Fig. 3. A rectangular dielectric slab and a piezoelectric actuator were inserted into the waveguide

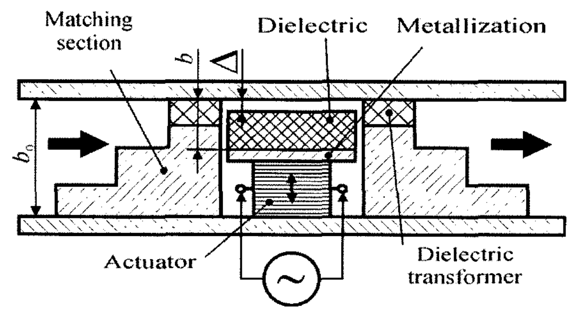


Fig. 3. Schematic drawing of side view of the phase shifter with air-dielectric sandwich structure and matching sections built in a rectangular waveguide.

and fixed at the center of inside wall of waveguide. The surface of dielectric slab facing the actuator was metallized with the silver paste. The dielectric slab and the matching sections are close to each other.

Depending on the dielectrics the impedance of the dielectric-moving part may vary up to 30 % under the device operation range. To facilitate its matching with the empty waveguide section, three-step Chebyshev transformer was used. Teflon insets were also used at the last step next to the air-dieleclayered part. Appropriate dielectrics other than Teflon can be used there to reduce impedance discontinuity. Perfect matching was not the objective of this study, but we experimentally tried to establish matching in medium displacement position. The design can be optimized using standard methodology taking the impedances of the air-filled part and the dielectric-loaded part of the waveguide as input variables[16].

By separating real and imaginary parts, the equation (2) can be transformed to a system of nonlinear equations with respect to the components of complex propagation constant, which could be solved numerically. Phase shifts for different dielectric constants and thicknesses of air gap were calculated based on these values. These simulations were performed for commonly used microwave dielectric ceramics that were employed in this work for experimental testing. Their properties are given in Table 1, and simulation results on phase shift as a function of the air gap thickness are shown in Fig. 4. The thickness and length of the dielectric slab are assumed to be 2 mm and 10 mm, respectively.

It seems generally that higher dielectric constant is preferred for larger phase shift. However, two effects prevent the use of very high dielectric constant material. Firstly, microwave propagates mostly in the dielectric plate with air gap practically ineffective. It is demonstrated in Fig. 4 that phase shift for $SrTiO_3$(ST) with dielectric constant ε =300 is less than that for BLT with ε =85, as the air gap exceeds 20 μm. Secondly, most of the phase shift occurs in the very narrow range of air gap particularly with high dielectric constant materials, which makes the

Table 1. Microwave dielectric ceramics tested for the air-dielectric sandwich structure at 10 GHz.

Material	ε'	$\tan\delta$
Al_2O_3	11.6	$0.7 \cdot 10^{-4}$
(Mg, Ca)TiO_3	21	$2 \cdot 10^{-4}$
$BaTi_4O_9$	37	$3 \cdot 10^{-4}$
Ba(La, Sm)$_2Ti_4O_{12}$(BLT)	85	$2 \cdot 10^{-3}$
$SrTiO_3$(ST)	300	$0.5 \cdot 10^{-2}$

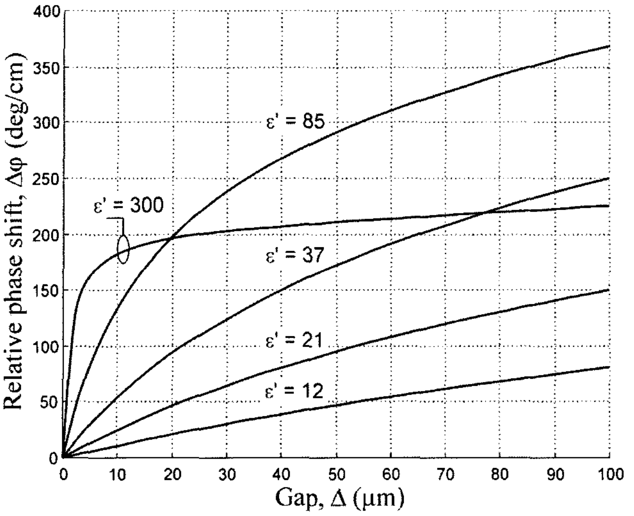


Fig. 4. Simulation result of relative phase shifts at 10 GHz of the air-dielectric sandwich structure with different microwave dielectrics of 2 mm in thickness and 10 mm in length.

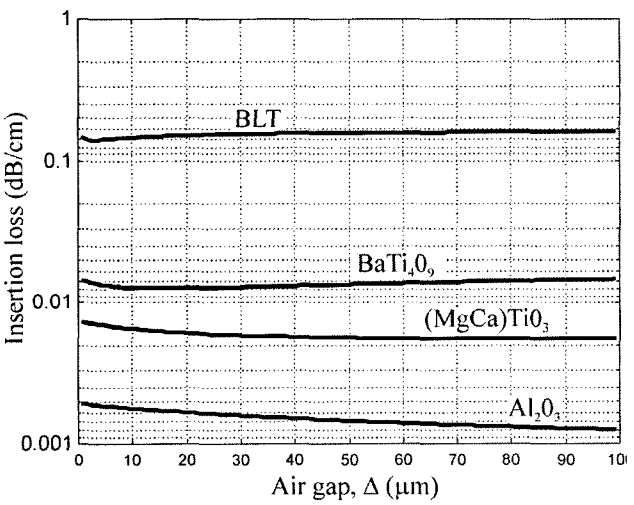


Fig. 5. Attenuation caused by dielectric loss calculated for the air-dielectric sandwich structure with different dielectric materials of 2 mm in thickness at 10 GHz.

practical application very difficult. For ST with its dielectric constant ε =300, for example, most of the phase shift occurs within the air gap less than 10 μm as shown in Fig. 4.

Insertion loss, which is very important for practical applications, was also analyzed. The loss due to dielectric material would dominate here assuming perfect metal of waveguide wall. In fact, modern microwave ceramics have very low loss, tan δ, typically less than 10^{-3}. Effective loss of the air-dielectric sandwich structure, however, depends on the thickness of air gap in a complex manner. Insertion loss determined by the numerical results is plotted in Fig. 5. Although the insertion loss shows some variations as a function of the thickness of air gap, it still remains less than 0.2 dB/cm in the X-band.

It is important to point out the problem associated with the transmission of high order modes. High order modes must be suppressed in phase shifters for reliable performance. Appearance of high order modes decreases transmitting energy. As dielectric material is introduced inside a waveguide, the cutoff frequency is reduced and high order modes can appear. For a waveguide filled with a dielectric material, the cutoff frequency can be expressed as[10]:

$$f_c = \frac{1}{2\pi\sqrt{\varepsilon_{eff}}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}, \tag{4}$$

where a is the width and b is the height of the waveguide cross section. High order modes can be suppressed by reducing the thickness of dielectric plate or the effective height of the waveguide following the equation (4). Increase in the cutoff frequency improves tuning capabilities of basic mode in turn as shown in Fig. 6. The major drawback of reducing the thickness might be the reduced ability in power handling.

Besides the mentioned possible sources of loss, it is important to point that device operation is based on control over the effective parameters of the sandwich structure. This means that matching will degrade in operation, resulting in higher return loss and thus lower S_{21}. Broadband matching, such as Chebyshev steps can tolerate wider impedances change, so they are preferable.

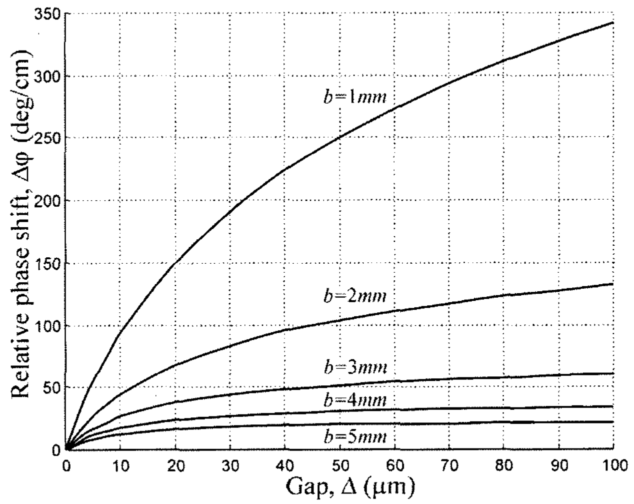


Fig. 6. Tuning capability versus the height b of active area calculated for the air-dielectric sandwich structure with a dielectric constant ε =37 at 10 GHz.

Ⅳ. Matching Transformer Performance Analysis

The key idea of the experiment is to control the effective dielectric constant of the air-dielectric composite by varying the air gap, thus perfect matching was not the goal. Nevertheless, practical application of the proposed idea assumes availability of design methodology. One of the possible approaches will be briefly described.

As the width of the waveguide remains constant and only the height changes, basic mode does not suffer from discontinuity. However, the real system will be affected by the redistribution of the higher order modes near the discontinuity inside the waveguide. Stepped transformer performance estimation can be performed using well-known modal analysis technique. Consider the junction of two waveguides of equal width a with different heights b_1 and b_2 respectively as shown in Fig. 7. Assume that TE_{10} wave is propagating from the section I ($z < 0$). Its field's components can be written as:

$$\begin{cases} \mathbf{E}_y = \sin\frac{\pi x}{a^I} e^{-j\beta^I_{11} z}; \\ \mathbf{H}_x = \frac{-1}{Z_1} \sin\frac{\pi x}{a^I} e^{-j\beta^I_{11} z}; \\ \mathbf{E}_x = 0; \\ \mathbf{H}_y = 0, \end{cases} \tag{5}$$

The propagation constant of TE_{mn} mode in the section I is

$$\beta^I_{mn} = \sqrt{k_0^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b_1}\right)^2} \tag{6}$$

and the wave impedance of this mode is

$$Z^I_{mn} = \frac{k_o \eta}{\beta^I_{mn}} = \frac{\omega \mu_o}{\beta^I_{mn}} \tag{7}$$

Boundary conditions can be obtained by equating field components from both sections at the junction. It is possible to obtain the required equation using E_x and E_y components. Besides the basic TE_{10} mode, there will be the infinite set of TE_{1n} modes scattering backwards in the section:

$$\mathbf{E}_x^- = \sum_{n=1}^{\infty} \frac{nA_{1n}}{b_1} \cos\frac{\pi x}{a} \sin\frac{n\pi y}{b_1} e^{j\beta^I_{1n} z};$$
$$\mathbf{E}_y^- = -\sum_{n=0}^{\infty} \frac{A_{1n}}{a} \sin\frac{\pi x}{a} \cos\frac{n\pi y}{b_1} e^{j\beta^I_{1n} z}, \tag{8}$$

where A_{1n} is unknown magnitude of the TE_{1n} mode. Similarly, the transmitted wave in the section II can be presented as the infinite set of TE_{1n} modes propagating towards the positive direction of the z axis:

$$\mathbf{E}_x^+ = \sum_{n=1}^{\infty} \frac{nB_{1n}}{b_2} \cos\frac{\pi x}{a} \sin\frac{n\pi y}{b_2} e^{-j\beta^{II}_{1n} z};$$
$$\mathbf{E}_y^+ = -\sum_{n=0}^{\infty} \frac{B_{1n}}{a} \sin\frac{\pi x}{a} \cos\frac{n\pi y}{b_2} e^{-j\beta^{II}_{1n} z}, \tag{9}$$

and propagation constant in this section will be

$$\beta^{II}_{mn} = \sqrt{k_0^2 - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b_2}\right)^2}, \tag{10}$$

while the wave impedance is

$$Z^I_{mn} = \frac{k_o \eta}{\beta^{II}_{mn}} = \frac{\omega \mu \mu_o}{\beta^{II}_{mn}} \tag{11}$$

At the junction point the transversal components of electromagnetic fields have to be equal.

Equating (8) and (9) and taking into account incident wave at z=0, it is possible to get infinite system of linear equations regarding to the mode magnitudes, A_{1n} and B_{1n}. Every A_{1n} will mean the reflection coefficient, while B_{1n} will be the transmission coefficient of the particular TE_{1n} mode. Having them it is possible to estimate scattering parameters of the junction. Then, transmission matrices technique can be used to estimate characteristics of cascaded steps.

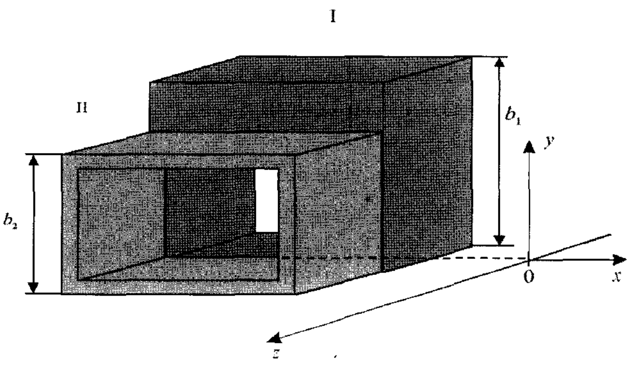


Fig. 7. E-plane step in the rectangular waveguide.

Ⅴ. Experimental Results and Discussions

Experimental setup was realized according to Fig. 3 with dielectric materials given in Table 1. Cross section of rectangular waveguide was partially filled by the right-angled plate, made from the low loss high-ε dielectrics. These dielectric plates were cut in a rectangular shape of 2 mm in thickness and 10 mm in length. To control the thickness(Δ) of the air gap, the plate is moved up and down by the piezoelectric actuator. The device matching is made by three-steps Chebyshev transformers[16]. Piezo-mechanical mini-actuator operates rapidly only in the case of rather small deformation. That is why the higher-ε dielectric should be used to decrease the air gap, following Fig. 4. Recent composite ceramic-metal actuators of "moonie" type[15] can provide mechanical displacement of about 100 μm that might be of non-hysteresis and very fast response time(< 10^{-5} s) because its resonant frequency is higher than 100 kHz. However, in this experiment, a commercial piezo-mechanical "stack-actuator" was employed. It provides displacement of 30 μm under the voltage of 150 V with the resonant frequency 30 kHz.

To guarantee accurate control of the thickness of air gap, we initially maximize the voltage applied to the actuator to make the dielectric plate contact metal wall of the waveguide. Then, reducing voltage gradually opens the air gap, which provides control of effective dielectric constants by increasing the thickness of air gap.

Some of experimental results of relative phase shifts for the air-dielectric sandwich structure are shown in Fig. 8. In actual measurements, the best performances of the device were achieved at 10.5 GHz rather than at the projected 10 GHz. As the amplitude-frequency characteristic shows no extrema around 10 GHz, it is reasonable to expect all figures to be reduced by factor of 0.95 since phase is proportional to frequency. Higher dielectric constant materials show larger relative phase shifts, as expected. For instance, the phase shift of 200° was observed with the BLT microwave dielectric as the air gap changed by 30 μm.

As one may note the absolute values of relative phase shifts are smaller than the predicted by simulation according to Fig. 4. This happens because it is impossible to establish perfect contact of dielectric slab to the waveguide wall due to surfaces roughness, details mutual skew and tension etc. Thus initial segment of control curve at small gaps, where the most effective control is possible, is hard to use.

Measured scattering parameters are shown in Fig. 9 and

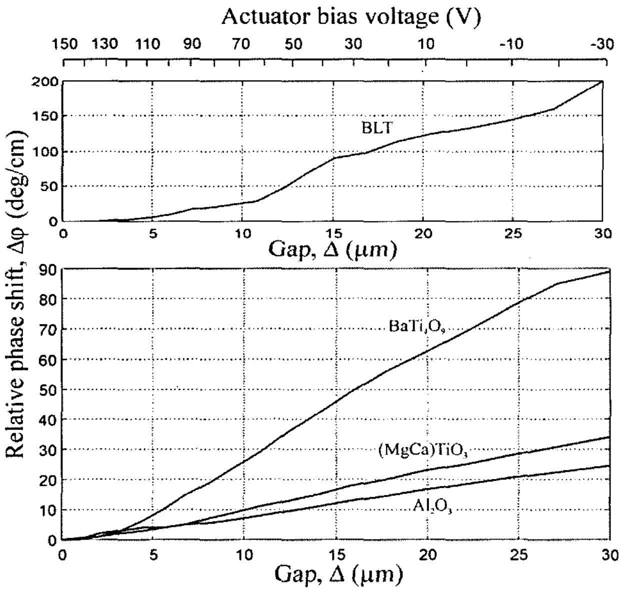


Fig. 8. Phase shift as a function of the thickness of air gap measured at 10.5 GHz.

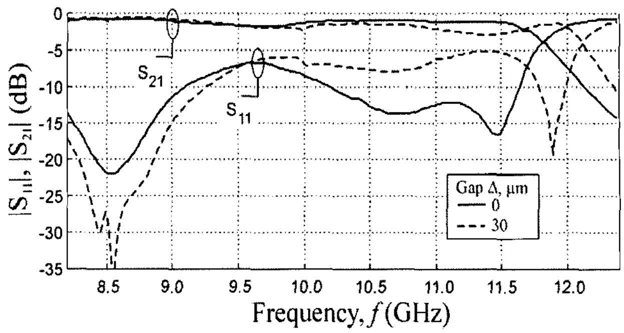


Fig. 9. Amplitudes versus frequency response for the sandwich structure with the dielectric material (Mg, Ca)TiO3(ε=21) of 2 mm in height and 10 mm in length.

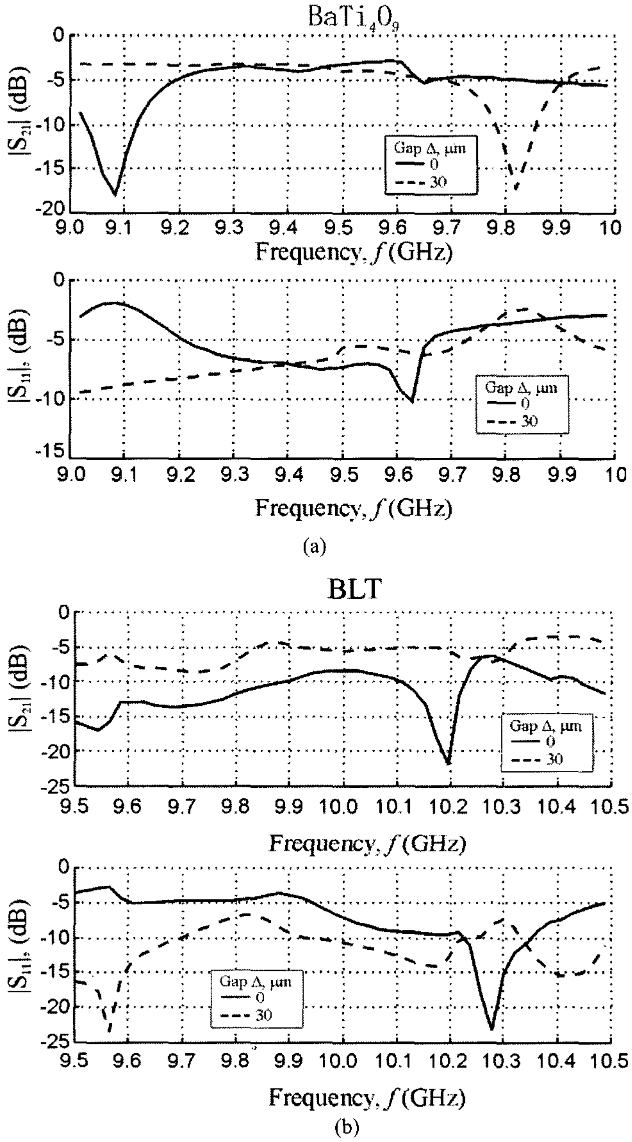


Fig. 10. Amplitudes versus frequency response for the sandwich structure with the dielectric material a) $BaTi_4O_9$(ε=37) and b) BLT(ε=85) of 2 mm in height and 10 mm in length.

10. In the case of (Mg, Ca)TiO_3 in Fig. 9, insertion loss is less than 1.5 dB in most ranges of X-band though the matching doesn't seem to be optimized. Thus, one can conclude that this device shows negligible insertion loss since low loss dielectric materials are used and intrinsic material properties are not disturbed. However for higher-permittivity materials shown in Fig. 10, insertion losses are kept below 3 dB since for high permittivity materials it is harder to get very broadband matching because the wave suffers from severe impedance differences over most of the X-band waveguide frequency range.

One of the most advantageous points of the proposed device is its flexibility in design. Longer dielectric slab induces lager phase shift. Higher dielectric constant requires smaller variation in the thickness of air gap. Small initial air gap increases the sensitivity of phase change. At the frequency of 40 GHz phase shift per centimeter of moving plate will be increased in 4 times in comparison with 10 GHz shown in Fig. 8. Although in the proposed design the dielectric plate is moved, it is possible also allow to fix the dielectric plate on the upper wall of waveguide, and control the thickness of air gap by moving a metal plate attached to the piezo-actuator.

Ⅵ. Conclusions

A new type of electrically tunable phase shifter was developed with conventional microwave dielectric ceramics and a piezoelectric actuator. The adjustment of air gap, created by a dielectric plate using an electromechanical actuator inside a waveguide, induced the phase shift of transmitting microwave signals. Variation in the thickness of air gap by tens of micrometers was enough to induce the reasonable phase shift with low loss for practical applications. Phase shifters made of 10 mm long dielectric plate with air gap changes by 30 μm showed the phase shifts of 20～200° at X-band. Since commercial piezoelectric actuator operates with the response time of microseconds, the present phase shifter can be applied for modern microwave systems where high operating speed is essential. Dielectric material with higher dielectric constant was preferred since the same variation in the thickness of air gap produces larger phase shift. Impedance matching, however, becomes difficult as dielectric constant becomes too high. Because the presented phase shifter does not alter any intrinsic properties of material, no fundamental limitation is expected in the operation frequency. It can be extended toward millimeter wave applications, where dielectric materials with $\varepsilon = 10 - 20$ and low loss seem to be adequate. In this case actuator should control much smaller gap of about less than 10 μm, so it can be faster and has smaller physical sizes.

The authors would like to thank the Korea Institute of Science & Technology Evaluation and Planning (KISTEP) for the financial support through the project, "Microwave dielectrics and components for telecommunication and radar system (M60203000052-04A0100-07810)."

References

[1] R. V. Garver, *Microwave Diode Control Devices*, Norwood, MA: Artech House, 1976.

[2] C. F. Campbell, S. A. Brown, "A compact 5-bit phase-shifter MMIC for K-band satellite communication systems", *IEEE Trans. Microwave Theory Tech.*, vol. 48, no. 12, pp. 2652-2656, Dec. 2000.

[3] K. Maruhashi, H. Mizutani, and K. Ohata, "A Ka-band 4-bit monolithic phase shifter using unresonated FET switches", *IEEE MTT-S Int'l, Microwave Symp. Dig.*, pp. 51-54, 1998.

[4] T. -Y. Yun, K. Chang, "A low-loss time-delay phase shifter controlled by piezoelectric transducer to perturb microstrip line", *IEEE Microwave Guided Wave Lett.*, vol. 10, no. 3, pp. 96-98, Mar. 2000.

[5] G. M. Rebeiz, G. -L. Tan, and J. S. Hayden, "RF MEMS phase shifters: design and applications", *IEEE Microwave Magazine*, vol. 3, pp. 72-81, Jun. 2002.

[6] J. R. Bray, L. Roy, "Development of a millimeter-wave ferrite-filled antisymmetrically biased rectangular waveguide phase shifter embedded in low-temperature cofired ceramics", *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 7, pp. 1732-1739, Jul. 2004.

[7] R. C. Hansen, "Scanning Antennas", *Encyclopedia of Electrical and Electronics Engineering*, J. G. Webster, Ed., New York: John Wiley & Sons, p. 685, 1999.

[8] S. K. Koul, B. Bhat, *Microwave and Millimeter Wave Phase Shifter Volume I: Dielectric and Ferrite Phase Shifters*, Artech House, 1991.

[9] V. K. Varadan, K. A. Jose, V. V. Varadan, R. Hughes, and J. F. Kelly, "Ceramic phase shifters for electronically steerable antenna systems", *Microwave Journal*, vol. 35, pp. 118-127, Jan. 1992.

[10] A. W. Scott, *Understanding Microwaves*, John Willey & Sons, 1993.

[11] D. L. Rascoe, A. L. Riley, J. Huang, V. Lubecke, and L. Duffy, "Ka-band MMIC beam steered transmitter array", *IEEE Trans. Microwave Theory Tech.*, vol. 37, no. 12, pp. 2165-2168, Dec. 1989.

[12] B. Kim, S. Baik, Y. Poplavko, and Y. Prokopenko, "Epitaxial BST thin film as microwave phase shifter", *Integr. Ferroelect.*, vol. 34, pp. 207-214, 2001.

[13] T. -Y. Yun, K. Chang, "Piezoelectric-transducer-con-

trolled tunable microwave circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 5, pp. 1303-1310, May 2002.

[14] T. -Y. Yun, Kai Chang, "A low-cost 8 to 26.5 GHz phased array antenna using a piezoelectric transducer controlled phase shifter", *IEEE Trans. Antennas Propagat.*, vol. 49, no. 9, pp. 1290-1298, Sep. 2001.

[15] Y. Poplavko, Y. Prokopenko, V. Molchanov, and A. Dogan, "Frequency-tunable microwave dielectric resonator", *IEEE Trans. Microwave Theory Tech.*, vol. 49, no. 6, pp. 1020-1026, Jun. 2001.

[16] C. A. Balanis, *Advanced Engineering Electromagnetics*, John Wiley & Sons, pp. 394-409, 1989.

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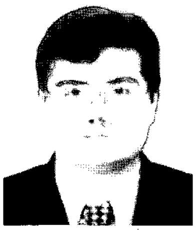
Victor Kazmirenko

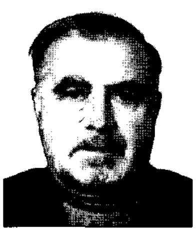


He received the M.S.(1999) and Ph.D. (2003) degrees from Kiev Polytechnic Institute, Ukraine. He is currently with physical & biomedical electronics department of National Technical University of Ukraine "KPI" as Senior Lecturer. In 2001-2003 he worked with POSTECH as research fellow. His main research interests are in the area of numerical methods, computational electromagnetics and microwave circuits.

Beomjin Kim

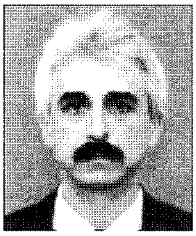
He received his B.S. in 1998, M.S. in 2000, and Ph.D. in 2005 in materials science and engineering from Pohang University of Science and Technology. His research interest includes ferroelectric thin films for microwave tunable devices.

Yuriy Poplavko



He received the Engineer and Ph.D. degrees from Kiev Polytechnic Institute, Ukraine. He worked in microwave high dielectric constant materials, ferroelectrics, piezoelectrics pyroelectrics study and applications, and in 1976 received a degree of Doctor of Science in Solid State Physics. He is currently working as Prof. Dr. in Microelectronics Department of National Technical University of Ukraine teaching Physics of Dielectrics and Solid State Physics. His research interests are microwave controlled devices, microwave dielectric spectroscopy, physics of pyroelectricity and piezoelectricity. He published 8 books and brochures, and more than 200 papers. Last years he gave lectures in Portugal, Germany, USA, Japan and South Korea.

Yuriy Prokopenko



He was born in Chernovtsi, Ukraine, in 1962. He received the engineering diploma and the Ph.D. degrees from Kiev Polytechnic Institute, Ukraine, in 1987 and 1991, respectively, both in electronics. He is currently working as Assoc. Prof. in Biomedical Electronics Department of National Technical University of Ukraine. In 1998 he joined the Tescom Co., S. Korea, where he is involved with design, modeling and characterization of TEM cells as well as antenna measurement technique for mobile communication systems. His main research interests are in the area of numerical methods, computational electromagnetics and microwave circuits.

Sunggi Baik

He received the B.S. degree in Metallurgical Engineering from Seoul National University, Korea, in 1971, and Ph.D. degree in Materials Science from Cornell University, USA, in 1981. He is currently working as a Professor of Dept. of Materials Science and Engineering in Pohang University of Science and Technology (POSTECH). He worked as a Director of Pohang Accelerator Laboratory(PAL), Pohang, Korea, in 2000-2004. His main research interests are characterization of nano-domain structures of ferroelectric thin films, and synthesis & sintering of nano-sized particles. He is also interested in ferroelectric thin films for microwave tunable devices.