J Electroceram (2006) 17:427–432
DOI 10.1007/s10832-006-9347-9

Microwave slot transmission lines based on ferroelectric films tunable through low bias voltage

I. G. Mironenko · Chong-Yun Kang · S. F. Karmanenko · A. A. Ivanov · A. A. Semenov · O. V. Sinjukova

Received: 5 August 2005 / Revised: 10 January 2006 / Accepted: 30 May 2006

Abstract The modifications of microwave slot transmission lines formed on the (Ba,Sr)TiO_3 ferroelectric films were investigated to realize high quality factor millimeter-wavelength devices tunable by low bias voltages. The narrow inner electrodes inserted to a slot line form the novel type of the transmission lines, which was called *multislot line* (MSL). The MSL short-circuited and tunable resonators were tested at frequency ∼30 GHz. The MSL phase shifter merit factor was evaluated higher than 100 degree/dB at bias voltage lower 100 V. The comparatively high quality factors of tunable MSL resonators and phase shifters evidence on real prospects of novel topology approach to the development of such microwave devices as tunable band-pass filters and electronically steerable antennas.

Keywords Ferroelectric films · Tunable microwave filter · Slot transmission lines · Multislot resonator

Introduction

Various radioelectronic systems, such as cellular and satellite communication stations, mobile navigation devices, radars, wireless global and local area networks require simple, reliable and inexpensive tunable components [1, 2]. This need can be filled to a great extent by replacing complex active devices with microwave (MW) tunable transmission lines and circuits made with use of thick and thin films having nonlinear physical properties, such as integrated ferroelectrics. Therefore many laboratories in the world develop the following integrated microwave tunable devices based on ferroelectric films: tunable band filters, phase shifters, voltage controlled oscillators, electronically-steerable antennas (ESA) [2–8].

There are two main approaches to develop microwave tunable devices based on the ferroelectrics components: (i)—the conventional circuits and topologies having high quality factor supplied with the lumped tunable components, such as varactors [4, 5, 8], (ii)—the microwave transmission lines formed on the surface of ferroelectric films grown on the dielectric substrates [2, 3, 6, 7, 9]. Microwave tunable slot and coplanar transmission lines are widely used for various planar microwave devices. The considerable lack of the mentioned transmission lines is connected with the comparatively high bias voltage (U_b), which is required for necessary variation of the dielectric constant. A lowering of (U_b) can be implemented only by means of decreasing of a gap between the electrodes that leads to an enhancement of microwave signal attenuation in the electrodes possessing the finite conductivity. To provide a bias voltage less than 100 V a gap between the electrodes on the surface of $Ba_xSr_{1-x}TiO_3$ (BST) ferroelectric films has to be lower than 10 μm. The modeling and experimental results show that signal attenuation in the slot and coplanar lines formed on the BST ferroelectric films and the gap width 10 μm between the electrodes are too high, so the formation of microwave devices based on such components has not a sense.

To overcome the contradiction between the microwave losses and the bias voltage applied to the electrodes of planar transmission lines we have proposed the multislot transmission line—MSL [9, 10]. The novel multislot transmission line (MSL, see Fig. 1) opens new opportunities to

I. G. Mironenko · S. F. Karmanenko (✉) · A. A. Ivanov · A. A. Semenov · O. V. Sinjukova
Electrotechnical University (ETU), St. Petersburg, 197376, Russia
e-mail: sfkarmanenko@mail.eltech.ru

C.-Y. Kang
Korea Institute of Science and Technology (KIST), Seoul 136-791, Korea

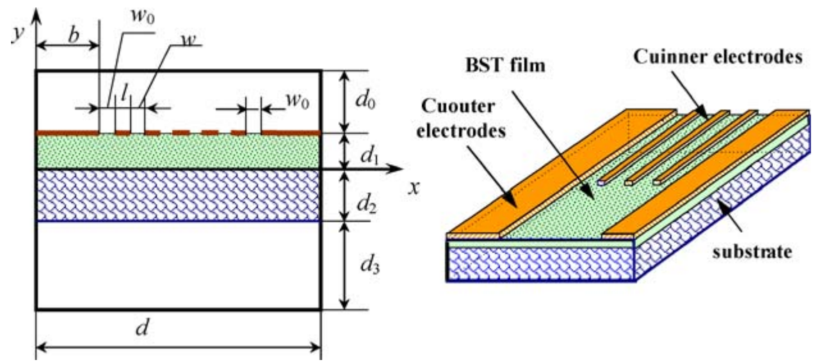

Fig. 1 The model representation of the design of microwave multislot transmission line formed on the surface of BST ferroelectric film

optimize the propagation constant $\gamma = \gamma' - j\gamma''$ and U_b using the variations of ferroelectric film thickness d_2 and its characteristics—dielectric permittivity ε, the dielectric loss factor tan δ; number N and width of the inner electrodes (l) and the gaps (w, w_0) between them.

In this work we present the results of electrodynamic analysis and experimental characteristics for various MSL and we discuss the prospects of tunable microwave devices such as phase shifter and tunable band-pass filter in the millimeter wavelength range.

The design and electromagnetic analysis of multislot transmission lines

The bias electrical field in multislot lines is formed by narrow inner and outer electrodes and the gaps between them. The layered structure "ferroelectric film—substrate" can be presented as a waveguide of lowered surface electromagnetic waves (see Fig. 1a). A rectangular area is restricted either by a couple of vertical ideal conducting walls or by the magnetic walls. A choice of the wall type does not play an important role at enough long distance from the structure axis line, i.e. much longer than wave length. However at the conditions of symmetrical or anti-symmetrical wave excitation in the pair of the coupled lines the choice of the wall behavior has the principal character.

The analysis of electromagnetic waves propagation in the presented transmission lines was carried out basing on full-wave approach. The main analysis goals were the simulations of the canalized electromagnetic wave phase velocity (wave length); the wave impedance; and propagation parameter γ that includes the attenuation parameter γ'' composed of the electromagnetic losses γ''_σ in the electrodes and γ''_δ—the electromagnetic losses in the dielectric layers of the transmission line. The electromagnetic field in all presented designs of the transmission lines has the hybrid character and that has three components of electric field E_x, E_y, E_z and three components of magnetic field H_x, H_y, H_z. Therefore the electromagnetic analysis has to be conducted in the complete orthogonal basis, which is formed by electromagnetic vector potentials. Using the orthogonal basis restricted by the ideal electric or magnetic walls it is expedient to determine two vector potentials in every area of the transmission line cross section: magnetic $A = \bar{e}_y A(x, y) \exp(-j\gamma)$; and electric potential $F = \bar{e}yF(x, y) \exp(-j\gamma)$, where γ is the required wave propagation parameter. This kind of the field potentials creates a complete orthogonal system of LSE and LSM oscillation modes in rectangular waveguide with partial dielectric filling. The boundary conditions at the dielectric and metallic walls demands the equivalence of the tangent electric components ($E_x = E^{(i)}_{x\ \mathrm{LSE}} + E^{(i)}_{x\ \mathrm{LSM}}$; $E_z = E^{(i)}_{z\ \mathrm{LSE}} + E^{(i)}_{z\ \mathrm{LSM}}$) [9]. The Fourier analysis of the boundary conditions leads to the integral equations with the required functions $f^i_k(x)$ and $g^i_k(x)$ that are the distributions of the fields E_x and E_z respectively in the k-gap.

To solve the integral equations the Galerkin approach was used. Thus the uniform equation system respectively unknown coefficients and was obtained. The zero value of the system determinator gives the required value of $\gamma = \gamma' - j\gamma''_\sigma$. The complete attenuation parameter includes also γ''_δ caused by the dielectric filling and its tangent of dielectric loss angle—tan δ. The following expression was used for the "dielectric" part of attenuation parameter:

$$\gamma''_\delta \cong \varepsilon \frac{\partial \gamma}{\partial \varepsilon} \tan \delta. \tag{1}$$

We simulated the wave impedance of various transmission lines using the following formula: $Z_0 = \frac{U^2}{2P}$, where U is the high frequency amplitude between the electrodes, P is the power transmitted through the line. Thus, the electrodynamic analysis of the considered transmission lines was performed basing on the full-wave approach with extremely minimal deviations from strict physical model.

The simulation and experimental results for MSL resonators formed on BST films

Among known ferroelectric materials the perovskite $Ba_x Sr_{1-x}TiO_3$ films with $x = 0.4\ 0.6$ are most expediently used

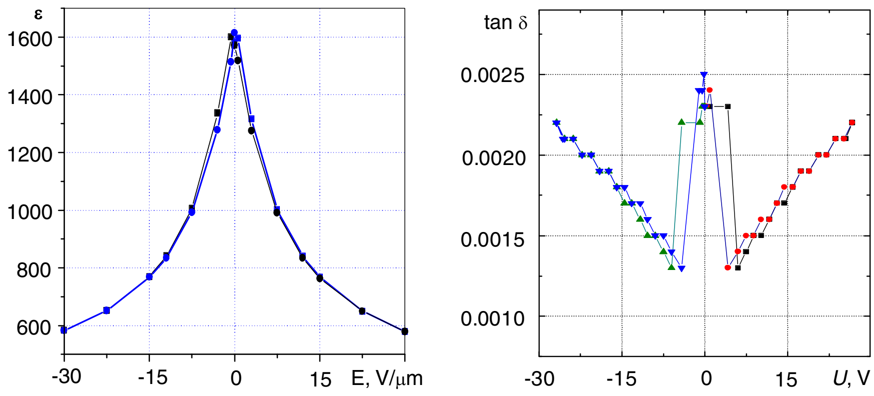

Fig. 2 The dielectric characteristics (ε and tan δ) versus bias DC electrical field (E_b) of BST films grown on sapphire substrate. The measurements were made on the planar capacitors with the gap width 7 mm

to obtain the tunability coefficient $n = C(U = 0)/C(U_{max})$ about 1.5 2.0 at DC bias electric field $E_{max} \sim 10\ V/\mu$m [2, 4, 7, 11]. In this work we used BST films grown in the process of cathode reactive sputtering of the powder sintered target [11]. Figure 2 shows the dielectric characteristics and tunability of the typical BST film grown on the sapphire substrate. The film characteristics were determined using the measurements of planar capacitor topologies, which had the gap width between the electrodes 5–7 μm. We measured capacitance variations under action of bias voltage up to 200 V and high frequency (1 MHz) signal of 0.1 V amplitude, tangent of dielectric loss angle *(*tan δ, see Fig. 2b) and temperature dependencies of C and tan δ) [11, 12]. The dielectric loss factor was varied from ~0.002 at 1 MHz, about 0.01–0.02 at frequency 10 GHz, and to 0.03–0.04 at 30 GHz. The BST film parameters were used for the simulations of the frequency response of ordinary slot and MSL planar topologies.

The simulations of the amplitude and phase frequency dependencies (propagation characteristics) of MSL resonators were carried out for the following regimes: the frequency around 30 GHz, BST film thickness was changed from 100 to 1000 nm; the dielectric constant $\varepsilon = 750$–1500 (see Fig. 2a).The simulation results of the propagation coefficient consisted of the real (γ') and imaginary (γ'') parts in dependence on the partial slot number N in the MSL are presented in Fig. 4. The imaginary part of the propagation constant is caused only by the attenuation in the electrodes ($\sigma = 5 \times 10^7$ (Om·m)$^{-1}$.We considered the situation, in which the gap and inner electrode have the same width: $w = s = 5\ \mu$m. The data presented in Fig. 4 give a possibility to evaluate the induced attenuation in the MSL with various gaps.

The dependencies in Fig. 3 show that the gradient $\partial\gamma/\partial\varepsilon$ is approximately the same in every point and it is near to 10^{-3}, therefore it is possible to estimate the total attenuation in the transmission line. If the MSL has nine gaps, BST dielectric permittivity equals to 1500, then $\gamma''_\sigma = 0.045$ dB/mm, and $\gamma''_\delta \approx 1.5 \cdot$ tan δ, see the formula (1). Using the average tan δ value of BST films in the band 30–40 GHz, which was presented in such works as [2, 4–8] — tan $\delta = 3 \times 10^{-2}$, we obtain $\gamma''_\delta \approx 0.40$ dB/mm. Thus, "electrode contribution" to the total attenuation parameter does not exceed 10% from the attenuation caused by the dielectric mechanism. We compared the obtained result with the parameters of ordinary slot line with $w = 5\ \mu$m based on the BST film with same tan δ. The simulation gave the result $\gamma''_\sigma = 1.0$ dB/mm for

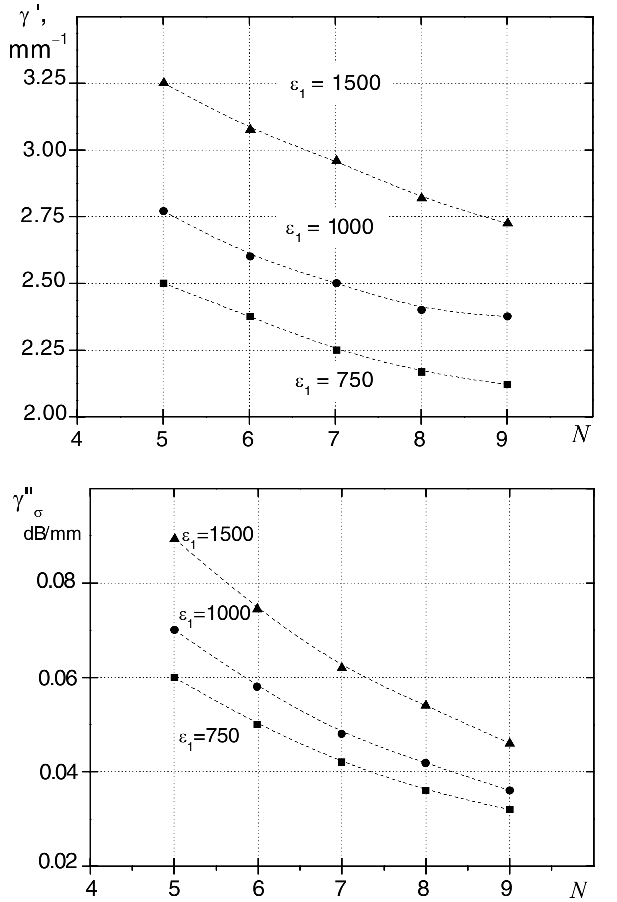

Fig. 3 The dependence of the propagation coefficient $\gamma = \gamma' - j\gamma''$ on the number of the inner electrodes inserted to the multislot transmission line: (a) the real part of the propagation coefficient γ' for various values of the dielectric permittivity; (b) the imaginary part — γ'' for various values of the dielectric permittivity

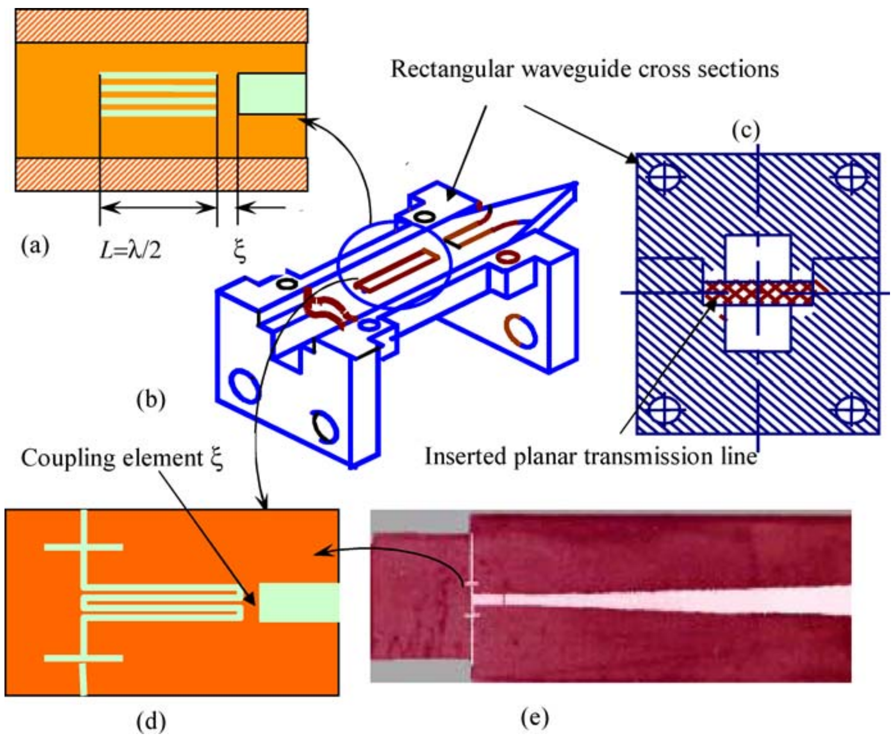

Fig. 4 Design of half-wavelength resonator based on the MSL topology and rectangular metalic waveguide. (a) the sketch of λ/2 slot resonator formed by the section of short-circuited MSL; (b) the metallic waveguide with the inserted planar MSL resonator; (c) the cross section of the metalic waveguide with the inserted resonator structure; (d) the λ/2 planar MSL resonator supplied with the electrodynamic short circuit on the left edge and the coupling element on the right edge; (e) the image of the slot line topology consisted of λ/2 resonator and the matching slot line

$\varepsilon = 1500$, and $\partial\gamma/\partial\varepsilon \approx 2 \times 10^{-3}$ [9]. The dielectric contribution $\gamma''_\delta \approx 0.78$ dB/mm, and the total attenuation parameter of ordinary narrow slot line $\gamma'' \approx 1.78$ dB/mm is about four times higher in comparison with the same parameter for MSL line — $\gamma''_\delta \approx 0.40$ dB/mm.

Experimental MSL characteristics were investigated at frequency around 30 GHz. We have measured the propagation characteristics λ/2 ordinary slot and MSL resonators in various regimes. Figure 4 presents the design of the measuring assemblies. The metallic rectangular waveguide (Fig. 4b and c) was used as the device measuring body, which was consisted of two parts. The electrode/BST/substrate sample with the width 6 mm was placed into one part of the metallic waveguide, which was covered by another waveguide part. The topology of short circuited MSL resonator is presented in Fig. 4(a) and the tunable resonator is shown in Fig. 4(d). We used the simplest MSL topology with three inner electrodes of 30 μm width, which were separated by four partial slots with the same width —30 μm. The MSL resonators were coupled with matching slot line through the coupling microstrip element (ξ), see Fig. 4(d) and (e).

The transmitting and reflective regimes were used for the measurements of propagation characteristics S_{11} and S_{12}. Figure 5(a) presents the frequency dependencies of the transmission (propagation) coefficients that confirm the correctness of the performed measurements. The quality factor of MSL resonators was varied between 80 and 120. Figure 5(b) presents the shift of resonance frequency under action of bias

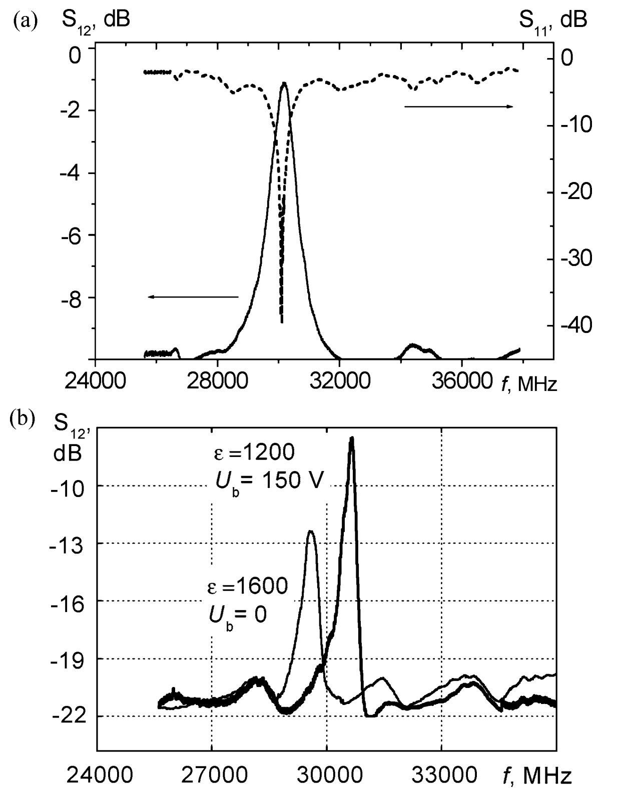

Fig. 5 The frequency dependencies of the transmission characteristics (S_{11} and S_{12}) for the MSL resonators; (a) short-circuited $\lambda/2$ MSL resonator consisted of three inner electrodes and four partial sketches; (b) the characteristics of tunable planar resonator with the width of partial slot 30 μm The bias voltage ~150 V lead to the shift of resonance frequency on ~1 GHz around 30 GHz

Table 1 The characteristics of tunable MSL resonators for the varied dielectric constant and BST film thickness

Dielectric permittivity, ε_1	Resonance frequency, f_0, GHz	The resonator quality factor, Q_0	Resonator band-width $\Delta f_{0.7}$, GHz
Ferroelectric film thickness — 500 nm; resonator length — 1.5 mm			
1500	30.00	40.0	0.750
1250	32.00	42.5	0.753
1041	33.65	46	0.730
868	35.50	49	0.720
723	37.0	53	0.700
Ferroelectric film thickness — 100 nm; resonator length — 2.0 mm			
1500	29.30	79	0.37
1000	30.00	97	0.31
830	30.56	105	0.29
690	31.62	118	0.26
570	31.44	129	0.24
480	31.82	136	0.23

electric field ∼5 V/μm applied to the electrodes. The bias voltage for the chosen topology (the width of partial slots is 30 μm) was about 150 V. An increase of the quantity of the partial slots in the slot line and a decrease of its width lead to a lowering of required bias voltage and improvement of the resonator quality factor.

Development of tunable microwave band-pass filters and phase shifters based on the MSL topologies

Microwave devices, such as tunable band-pass filter, phase shifter, based on MSL and IPL topologies allow controlling amplitude and phase transmission characteristics by means of comparatively low bias voltages without an increase of signal attenuation, which inevitably arises in the electrodes of the slot and coplanar lines with narrow gaps—less than ∼30 mm at 30 GHz.

We can evaluate the MSL phase shifter merit factor, which equals to the ratio of differential phase shift to the attenuation on the length unit: $Q_{ps} = \Delta\gamma'/\gamma''$, where $\Delta\gamma'$—the difference of the propagation coefficient in the variation region of the ferroelectric film dielectric permittivity. As the dependence of the propagation coefficient versus the variation of the dielectric permittivity has the practically linear behavior (see Fig. 4a) for the MSL, the quality factor can be evaluated by the following equation: $\Delta\gamma = [\varepsilon(0) - \varepsilon(E)]\partial\gamma/\partial\varepsilon$, where $\varepsilon(0)$ and $\varepsilon(E)$—the BST film dielectric constant corresponded for the electric field. The attenuation in the MSL electrodes can be neglected, so $\gamma'' \cong \gamma''_\delta$, and the phase shifter merit factor can be expressed as follows:

$$Q_{ps} = 8.69\left[\frac{\varepsilon(0)}{\varepsilon(E)} - 1\right]\frac{1}{\tan\,\delta}, \quad \text{degree/dB}$$

If $\varepsilon(0)/\varepsilon(E) = 1.5$ and $\tan\delta = 3 \times 10^{-2}$, the $Q_{ps} \approx 10^2$ degree/dB. This expression does not account the dependence of the dielectric loss factor on the bias voltage; however this weak dependence can change the merit factor only on several per cent. The value 100 degree/dB is very optimistic for the development of the phase shifters for millimeter wavelength region.

We evaluated the characteristics of tunable band-pass filters based on the coupled MSLs. The filter transmission characteristics are determined by the resonator quality factor; the resonators number; the coupling parameter; and the resonator property to shift the resonance frequency. The Table 1 presents the parameters of λ/2 resonators based on short-circuited MSL sections. We simulated the topology consisted of six partial slots (six gaps and five inner electrodes). The partial slots and the inner electrodes have the same width — $w = l = 5$ mm; the electrode conductivity $\sigma = 5 \times 10^7$ $(\text{Om}\cdot\text{m})^{-1}$; substrate dielectric constant $\varepsilon_2 = 9.8$, substrate thickness — 340 μm. The Table 1 contains the values of the resonator quality factor: $Q_0 = \frac{Q_\delta Q_\sigma}{Q_\delta + Q_\sigma}$.

The calculations were implemented with the loss factor of BST film—tan $\delta = 0.03$. The Table 1 data allow evaluates the tuning properties of the band-pass filter formed on the planar coupled resonators [13, 14] and the attenuation in the pass band. The filters with comparatively wide operative frequency range $d\omega = 0.2$–0.3 could be realized on the resonators formed on relatively thick BST films. The Table 1 shows that at $d_1 = 500$ nm, and $n = 2$ the own frequency pass band for MSL resonator ($\Delta f_{0.707}$) can be changed from 0.70 to 0.75 GHz. At the same time the resonance frequency can be shifted on 5 GHz. Thus, the bands quantity for the filter frequency range equals ∼7. The attenuation in the band is evaluated as follows $L \approx \frac{4.34\,m}{d\omega Q_0}$(dB) [13], where m is the resonators quantity in the filter design. For the average resonator quality factor $Q_0 \approx 45$ the attenuation in pass band

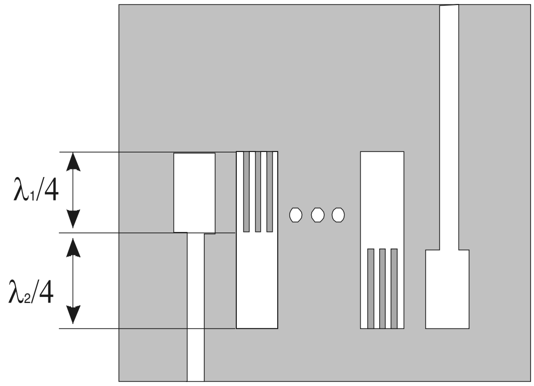

Fig. 6 The sketch of the topology of the planar tunable band-pass filter based on the coupled MSL resonators

for the filter consisted of four resonators is not more than 1.5–1.7 dB.

The filters with narrow frequency range — $\delta\omega \leq 0.1$ are developed on the coupled resonators patterned on BST films with lower thickness. The Table 1 shows that at BST film thickness $d_1 = 100$ nm $n = 1.7$–2.0 the average pass band is 0.32 GHz. As it can be seen from the Table 1, in this case the filter frequency range is 1.7 GHz; the bands quantity $\sim$5; and the attenuation in pass band $\sim$1.5–1.7 dB.

Figure 6 shows the planar topology of band-pass filter based on the coupled MSL resonators [14]. The topology includes ordinary slot lines placed at the topology borders, which play the role of feeding and matching lines. The MW signal from waveguide enters to the topology and to λ/4 resonator, which is coupled with MSL resonators through the metallic strip. Last MSL resonator is coupled with exit slot line.

The simulations results presented in the Table 1 evidence that MW tunable band-pass filters based on the MSLs resonators can be developed for various frequency range. The basic filter parameters pass are similar to the characteristics of the filters build up on the coupled microstrip resonators.

Summary

We presented the modeling representations, computational and experimental results of the investigations of novel microwave multislot and isoplanar transmission lines based on the ferroelectric films. The obtained results show that MSL and IPL topologies have the real practical prospects for the creation of high quality tunable devices such as phase shifters and tunable bandpass filters. The important advantages of the MSL and IPL transmission lines consists in that the effective control of the electromagnetic wave phase velocity can be implemented under action of comparatively low bias voltages (no more than 30 V). The lowering of bias voltage is achieved without the MW signal attenuation increase. We obtained the simulated characteristics of MSL phase shifter working at $f = 30$ GHz, which include very optimistic merit factor $\sim$100 degree/dB. A variety of the topology designs of microwave tunable bandpass filters were considered and the filters for narrow and wide frequency bands and ranges were presented. It was shown that to select the filter frequency band and its range the BST film of the required thickness (100–500 nm) has to be chosen. The most considerable advantages of the proposed transmission lines in comparison with the traditional ones are achieved in millimeter wavelength region, especially, at wavelength 35 mm.

Acknowledgment The work is supported by the Project KR-2005A134 financed through the Korea institute of science and technology—KIST and the project of the International science and technology center—ISTC # 2896.

References

1. K. Willey, *Microwave J.*, **45**(1), 114 (2002).
2. R. Romanofsky and A. Qureshi, *IEEE Trans. Mag.*, **36**, 3491 (2000).
3. M.J. Lancaster, J. Powell, and A. Porch, *Supercond. Sci. & Technol.*, **11**, 1323 (1998).
4. A. Kozyrev, V. Keis, V. Osadchy, O.Y. Buslov, and L. Sengupta, *Integr. Ferroelectrics*, **34**, 189 (2001).
5. E.G. Erker, A.S. Nagra, Yu. Liu, P. Periaswamy, T.R. Taylor, J. Speck, and R.A. York, *IEEE Microwave Guided Wave Lett.*, **10**, 10 (2000).
6. I.G. Mironenko, A.A. Ivanov, S.F. Karmanenko, and A.A. Semenov, *Integr. Ferroelectrics*, **49**, 63 (2002).
7. B.J. Kim, S. Baik, Y. Poplavko, Y. Prokopenko, J.Y. Lim, and B.M. Kim, *Integr. Ferroelectrics*, **34**, 207 (2001).
8. O.Ju. Buslov, V.N. Keis, A.B. Kozyrev, I.V. Kotel'nikov, and P.V. Kulik, *Tech. Phys.*, **75**(9), 89 (2005).
9. I.G. Mironenko and A.A. Ivanov, *Tech. Phys.*, **72**, 69 (2002).
10. I.G. Mironenko, S.F. Karmanenko, A.A. Ivanov, and A.A. Semenov, *Slot Line. Patent of Russian Federation* No2258279 (10.08.2005); PCT/RU2004/000150.
11. S.F. Karmanenko, A.I. Dedyk, N.N. Isakov, V.I. Sakharov, and I.T. Serenkov, *Integr. Ferroelectrics*, **49**, 207 (2002).
12. S.F. Karmanenko, A.I. Dedyk, A.A. Melkov, V.I. Sakharov, I.T. Serenkov, and Jowoong Ha, *J. Phys.: Condensed Matter*, **14**, 6823 (2002).
13. G. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters Impedance—Matching Network and Coupling Structures*—Artech House Books, Dedham, MA, 1980
14. I.G. Mironenko, A.A. Ivanov, A.A. Semenov, S.F. Karmanenko, and T. Inushima, *Ferroelectric*, **286**, 343 (2003).