DESIGN OF TUNABLE FERROELECTRIC FILTERS WITH A CONSTANT FRACTIONAL BAND WIDTH

Irina Vendik*, Orest Vendik*, Vladimir Pleskachev*, Alexey Svishchev*,

Roger Wördenweber **

* Electrotechnical University, St. Petersburg, 197376, Russia

** Forschungszentrum Jülich, D-52425 Jülich, Germany

Abstract — **The main principle of design of tunable ferroelectric filters with a constant fractional band width in the tuning range are discussed. The lumped ferroelectric capacitors are used as the tunable components of the microstrip filter. The limitation of the filter performance is determined by the commutation quality factor of the ferroelectric varactor. The influence of the loss factor of the ferroelectric capacitor is analyzed. The 3-pole 1% fractional band pass filter with 3 band width tuning range without a degradation of the characteristics is designed.**

I. INTRODUCTION

Tunable capacitors based on STO and BSTO ferroelectric films can be used as components of tunable band-pass filters. The generalized criterion is used for evaluation of limiting characteristics of the tunable filters: the commutation quality factor (CQF), which depends on both tunability and loss tangent of the ferroelectric capacitor [1,2]. The CQF for the ferroelectric capacitor is defined as

$$K = \frac{(n-1)^2}{n \cdot \tan\delta_1 \cdot \tan\delta_2}, \qquad (1)$$

where *n* is the tunability of the ferroelectric capacitor

$$n = \frac{C_1}{C_2} \qquad (2)$$

and $tan\delta$ is the loss factor: $\tan\delta_{1,2} = \omega C_{1,2} \cdot r_{1,2}$ determined by the values of the capacitance C_1 and C_2 and the series resistance r_1 and r_2 at the control voltage $V=0$ and $V=V_{con}$ correspondingly. For the planar tunable capacitors based on BSTO (room temperature) and STO (T < 100 K) films, the typical values of the parameters are $n = 2$ and $tan\delta = 0.01$. That corresponds to K = 5000. The best samples of the BSTO capacitors exhibit $tan\delta = 0.003$ and K = 15000. It was shown [1,3] that for a tunable N-pole filter, the figure of merit determined as the ratio of the shift of the central frequencies of the pass band of the filter to the average pass band ($\Delta\omega_{av} = \sqrt{\Delta\omega_1 \Delta\omega_2}$) is

$$F = \frac{\omega_{02} - \omega_{01}}{\Delta\omega_{av}} \approx \frac{1}{4N^2}\sqrt{K}. \qquad (3)$$

The figure of merit is strongly dependent on the CQF value and the filter order N. The equation (3) allows evaluating a range of tunability for a chosen filter order and the given CQF of the ferroelecric capacitors.

An important problem is to avoid the filter performance degradation in the tuning range. In this paper we derive an original approach to solving this problem and design the tunable filters with a constant fractional bandwidth in the tuning range.

If $tan\delta \geq 0.01$, the performance of the filter based on the tunable ferroelectric capacitors can degrade dramatically. This problem is investigated and discussed.

II. LIMITATION OF THE TUNABILITY RANGE OF THE FILTER

Using equation (3), one can find the range of the tunability of the N-pole filter evaluated by F i.e. by a number of averaged pass bands $\Delta\omega_{av}$ in the tuning range. The results are shown in Table 1.

Table 1

The figure of merit of the N-pole tunable filter for two different values of CQF

K	5000			15000			
N	2	3	4	2	3	4	5
F	4.4	2.0	1.1	7.7	3.4	1.9	1.2

The results of Table 1 allow concluding that the available planar ferroelectric capacitors with K ≤ 5000 cannot provide a wide tuning range of high order filters. For example, the 3-pole filter characteristic can be shifted along the frequency axis on 2 pass bands only. A suitable way to improve the filter tunability is to increase the CQF, which can be reached by using maximum control voltage, which does not exceed the breakdown threshold. Further we analyze 3-pole filters.

III. Theoretical Description of a Tunable Filter with a Constant Fractional Pass Band

The 3-pole filter prototype is shown in Fig. 1.

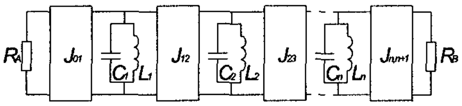

Fig.1. The diagram of the 3-pole pass band filter prototype.

The inversion characteristics of the J-inverters of the filter are described by the following equations [4,5]:

$$J_{01}=\sqrt{\frac{G_A b_1}{2g_0 Q_1}}, \tag{4}$$

$$J_{i,i+1}\Big|_{i=1\ldots n-1}=\frac{1}{2}\sqrt{\frac{b_i b_{i+1}}{Q_{L,i}Q_{L,i+1}}}, \tag{5}$$

$$J_{n,n+1}=\sqrt{\frac{G_B b_n}{2Q_n g_{n+1}}}, \tag{6}$$

where $b_i=\omega_0 C_i=(\omega_0 L_i)^{-1}$ is the admittance slope parameter of the i-th tank at the resonant frequency ω_0, Q_i is the loaded quality factor of the i-th tank of the Chebyshev filter prototype defined as

$$Q_i=\frac{g_i}{2\eta}, \tag{7}$$

g_i is the normalized parameter of the i-th element of the low pass Chebyshev filter prototype, and

$$\eta=\frac{\Delta\omega_f}{\omega_0} \tag{8}$$

is the fractional pass band of the band pass filter prototype.

In order to shift the pass band of the filter along the frequency axis, it is necessary to change the capacitance in the tanks in Fig. 1. A synchronous variation of the loaded quality factors in all the tanks leads to a change of the pass bandwidth. In order to provide the constant fractional pass bandwidth while tuning, the loaded quality factors have to be kept constant.

Let us introduce the characteristic function $\psi(\omega_0^{up})$:

$$\psi(\omega_0^{up})=\frac{Q_i(\omega_0^{up})}{Q_i(\omega_0^{low})}, \tag{9}$$

where $Q_i(\omega_0^{up})$ and $Q_i(\omega_0^{low})$ are the loaded quality factor of the i-th tank at the uppermost ω_0^{up} and the lowermost central frequency ω_0^{low} of the tunable band.

Using (7) and (8) one can present the characteristic function as

$$\psi(\omega_0^{up})=\frac{\Delta\omega_0^{low}\omega_0^{up}}{\Delta\omega_0^{up}\omega_0^{low}}, \tag{10}$$

where $\Delta\omega_0^{up}$ and $\Delta\omega_0^{low}$ are the filter band pass widths at the uppermost and the lowermost central frequency correspondingly.

For the tunable filter with a constant fractional pass band

$$\psi(\omega_0^{up})=1. \tag{11}$$

The equation (5) can be transformed into

$$J_{i,i+1}\Big|_{i=1\ldots n-1}(\omega_0^{up})=\frac{J_{i,i+1}(\omega_0^{low})}{\psi(\omega_0^{up})}\sqrt{\frac{b_i(\omega_0^{up})b_{i+1}(\omega_0^{up})}{b_i(\omega_0^{low})b_{i+1}(\omega_0^{low})}} \tag{12}$$

and for the filter containing identical tanks gives in combination with (11) the following equation:

$$\frac{J_{i,i+1}(\omega_0^{low})}{J_{i,i+1}(\omega_0^{up})}\cdot\frac{b_i(\omega_0^{up})}{b_i(\omega_0^{low})}=1. \tag{13}$$

The equation (13) is the main condition, which should be fulfilled for keeping the fractional bandwidth of the tunable filter constant in the range of tunability.

IV. Design of a Tunable Filter with a Constant Fractional Pass Band

For the filter structure based on coupled transmission line sections of length L terminated in the lumped tunable capacitors (Fig.2),

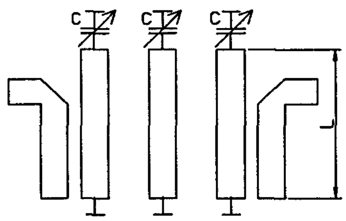

Fig.2. The tunable filter structure.

the equation (13) can be rewritten as follows:

$$\frac{1+2\Theta_0^{low}\frac{\omega_0^{up}}{\omega_0^{low}}\left[\sin\left(2\Theta_0^{low}\frac{\omega_0^{up}}{\omega_0^{low}}\right)\right]^{-1}}{1+2\Theta_0^{low}\left[\sin\left(2\Theta_0^{low}\right)\right]^{-1}}\cdot\frac{\omega_0^{low}}{\omega_0^{up}}=1 \tag{14}$$

where $\Theta_0^{low}=\frac{\omega_0^{low}L}{V_{ph}}$ is the electrical length of the transmission line section at the lowermost

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

central frequency. The left part of equation (14) depends on $\gamma = \dfrac{\omega_0^{up}}{\omega_0^{low}}$.

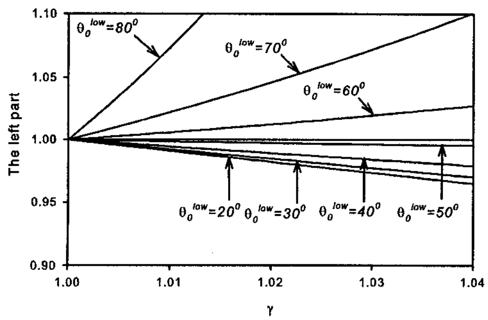

Fig. 3. The left part of equation (14) as the function of the central frequency relative shift.

It was found from equation (14) and Fig. 3 that the electrical length of the coupled lines $\Theta_0^{low} = 52^\circ$ provides shifting the frequency ω_0^{low} to $\omega_0^{up} + 4\Delta\omega_0^{low}$ (F = 4) with the constant pass-band. The capacitance at zero voltage is determined by the resonance condition at the lowermost frequency at $V = 0$:

$$\cot\left(\Theta_0^{low}\right) = z_0 \omega_0^{low} \cdot C(0), \qquad (15)$$

where $z_0 = 50$ Ohm is the characteristic impedance of the microstrip lines.

As an example, the 3-pole filter with 1% fractional pass band based on the structure shown in Fig.2 was analyzed. The simulated characteristics of the filter exhibited shifting the central frequency of the filter from ω_0^{low} (f_0^{low}=2GHz) to the higher value $\omega_0^{up} = \omega_0^{low} + 2\Delta\omega_0^{low}$ by the change of the capacitance from 1.2 pF to 1.1 pF. The further decreasing the capacitance led to increasing in-band insertion loss drastically. The necessary tunability of the capacitors providing the frequency shift $2\Delta\omega_0^{low}$ was 1.09 only. Actually, the ferroelectric capacitor reveals a much higher tunability. In order to use the tunable capacitor in a more effective way, we changed the coupling factor of the capacitor. For this purpose, another planar structure was suggested (Fig. 4): the capacitors were included between two transmission line sections of different length (L_1 = 2 mm, L_2 = 12.95 mm). The long line is shorted and the short line is open-ended. The simulated performance of the filter on alumina substrate (h = 0.5 mm and ε_r = 9.8) is presented in Fig. 5.

The tunability of the capacitors n = 2 is in need. The filter exhibits the tunability $\omega_0^{hi} = \omega_0^{low} + 2\Delta\omega_0^{low}$ and less than 1 dB in-band insertion loss even by using the capacitors with rather high loss-factor (tanδ = 0.01) and a

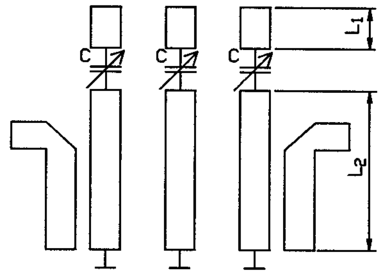

Fig. 4. The tunable filter structure with decreased coupling factor of the capacitors.

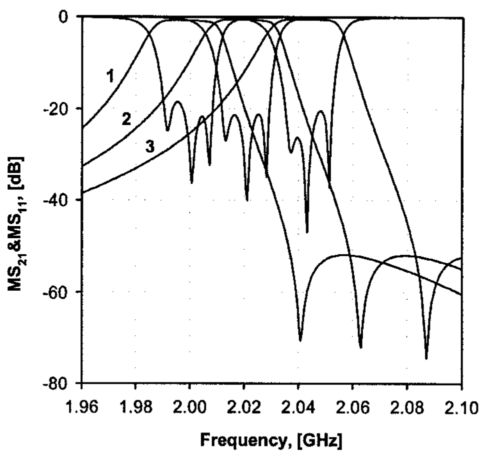

Fig.5. Simulated characteristics of the filter shown in Fig. 4. The tunable capacitors are used with C_1 = 1.2 pF (1), C_2 = 0.84 pF (2), C_3 = 0.6 pF (3), and $\tan\delta_1 = \tan\delta_2 = \tan\delta_3$ =0.01.

moderate value of CQF (K = 5000). The fractional bandwidth is constant in the tuning range. The figure of merit of the filter is F = 2.

The layout of the filter on sapphire substrate is shown in Fig. 6.

The filter performance depends on a variation of the control capacitance values in different resonators at the same control voltage applied to the capacitors. For example, if one needs to obtain the reflection coefficient less than 15 dB, the dispersion of the capacitor values should be no more than 1%. Fig. 7 shows how the filter performance depends on the dispersion of the capacitor values.

I. Conclusion

An original theoretical approach is suggested for a design of tunable narrow-band filters with a constant fractional bandwidth in the tuning range. A coupled microstrip structure of 3-pole

1% bandwidth filter with optimized coupling ratio for the capacitors seems to be promising. The simulation revealed a tunability of the filter with the figure of merit F = 2, a low in-band insertion loss and no change in fractional bandwidth in the tuning range.

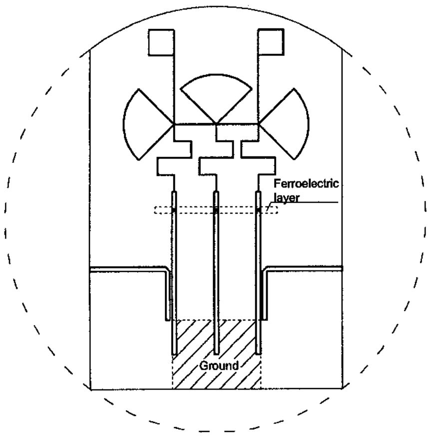

Fig.6. The layout of the tunable 1% band-pass filter on the 2" sapphire wafer.

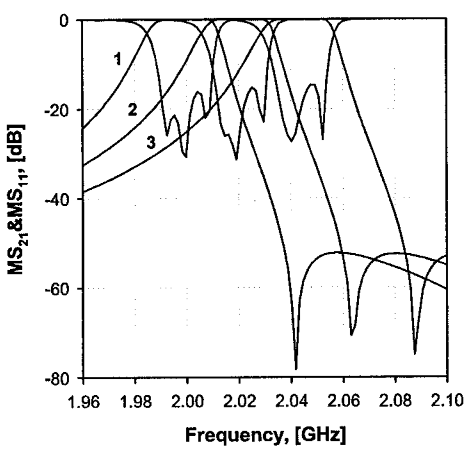

Fig. 7. Degradation of the filter performance under 1% dispersion of the tunable capacitor values: $C_1(0)$ = 1.2 pF, $C_2(0)$ = 1.19 pF, $C_3(0)$ = 1.21 pF

References

[1] I.B. Vendik, O.G. Vendik, E.L. Kollberg, Criterion for a switching device as a basis of microwave switchable and tunable components, Proc. of 29th EuMC, Vol. 3, 29th European Microwave Conference, Munich, Germany, 5-7 October, 1999, pp. 187-190.

[2] I. B. Vendik, O. G. Vendik, E. L. Kollberg, Commutation quality factor of two-state switching devices, IEEE Trans. on Microwave Theory and Tech., Vol. 48, No. 5, May 2000, pp. 802-808.

[3] O.G. Vendik, I.B. Vendik, V.V. Pleskachev, M.A. Nikol'ski, and M.L Khazov, Properties of tunable filters with ferroelectric capacitors, submitted to ISIF" 2001, *Colorado Springs, USA*.

[4] A. E. Znamenskiy, E. S. Popov, Electronically tunable filters, Sviaz, Moscow, 1979 (in Russian).

[5] G.L. Matthaei, L. Young, E.M.T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structures, Artech House, Norwood, 1980.