High-T_c Superconducting Planar Filter With Pseudo-Chebyshev Characteristic

Marina S. Gashinova, Maria N. Goubina, Guoyong Zhang, Igor A. Kolmakov, Yaroslav A. Kolmakov, and Irina B. Vendik, *Member, IEEE*

***Abstract*—This paper presents design and measurement results of a high-Tc superconducting planar filter based on a pair of coupled modified hairpin resonators considered to be a key constituent of the filter structure. This provides the filter characteristics, which are very close to the Chebyshev prototype of the same order.**

***Index Terms*—Hairpin, high-T_c superconducting (HTS) planar filter, microstrip.**

I. Introduction

PLANAR structure of high-T_c superconducting (HTS) filters based on planar transmission lines looks very attractive to be applied as receiving filters for mobile telecommunication base stations because of their small size and weight. The filters exhibit extremely low in-band insertion loss and high steepness of the characteristic at the edges of the passband [1]–[4]. Using a compact structure of a set of coupled resonators arranged as a regular array leads to decreasing filter selectivity as compared with the same order filter prototype [5], [6].

Two different design approaches are commonly used to realize the filter with the desired characteristics. The first one increases the filter order as compared with that prescribed by the prototype [1], [5]. However, the size of the microstrip filter resulting from this approach may be large and the frequency response is asymmetrical. The second approach is to introduce additional cross coupling between nonadjacent resonators, providing a quasi-elliptic filter characteristic [2], [6]. The quasi-elliptic filter performance can be achieved without a considerable enlargement of filter insertion loss and size by inserting coupling lines into the filter structure or by using a necessary arrangement of the resonators of a special form.

The goal of this paper is to suggest an original approach to the planar filter design, which is based on using the regular set of coupled double-resonator structures. Using such structure allows suppression of the undesired coupling between nonadjacent resonators and improvement of the filter performance. We present the results of simulation and experimental investigations of the bandpass filter without additional cross coupling, providing a steepness corresponding to the steepness of the Chebyshev prototype of the same order.

Manuscript received December 11, 2001; revised September 11, 2002.

M. S. Gashinova, M. N. Goubina, I. A. Kolmakov, Y. A. Kolmakov, and I. B. Vendik are with the Microwave Microelectronic Laboratory, Electrotechnical University, St. Petersburg 197376, Russia (e-mail: MWLab@eltech.ru).

G. Zhang was with the Department of Physics, Nankai Universtiy, Nankai District, Tianjin 300071, R.O.C. He is now with the Department of Electronics and Electrical Engineering, University of Birmingham, Birmingham B15 2TT, U.K.

Digital Object Identifier 10.1109/TMTT.2003.808588

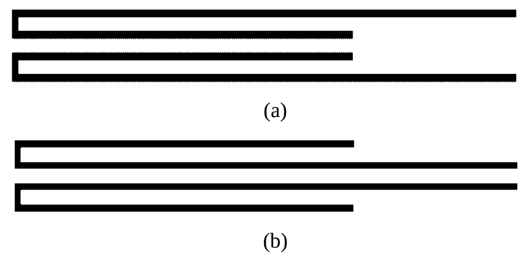

Fig. 1. Basic coupled structures of the resonators under investigation. (a) Electrical coupling. (b) Magnetic coupling.

II. Simulation and Design of the Filter

Conventional hairpin and hairpin-comb filters [7], [8] exhibit a nonsymmetrical frequency response and lower steepness as compared with the prototype prediction. The main target of this work is a design of the filter exhibiting the same slope parameter on both low- and high-frequency sides of the passband corresponding to the Chebyshev prototype.

The key constituent of the filter is a pair of coupled resonators. Fig. 1 presents the two basic coupled structures under investigation. It is clear that the fringing field provides the coupling between the resonators and the nature of the field determines the nature of the coupling. Evidently the magnetic fringing field is much stronger near the middle of the half-wavelength resonators, whereas the electric fringing field dominates on the open ends. The hairpin resonator used in the double-resonator structure is modified, having different lengths of the two arms. Intuitively, one can suggest that when short arms [see Fig. 1(a)] couple the resonators, the coupling should be mainly of an electrical nature. When the resonators are coupled by the long arms [see Fig. 1(b)], the coupling should be magnetic. The current distribution in the pairs of the resonators modeled by the software [9] illustrates this suggestion.

A full-wave EM simulator was used to simulate the frequency response of basic coupled structures at different coupling distances between the resonators. Furthermore, we determined the coupling coefficient by the two split resonant frequencies using the method described in [10].

The calculated results of the resonator-pair coupling coefficient as a function of the spacing for two different values of the substrate dielectric permittivity are presented in Fig. 2. One can see that the coupling coefficient for the basic structure [see Fig. 2(a)] exhibits a very rapid decay against the coupling distance and shows a strong dependence on value of the dielectric constant. The character of coupling coefficient of the structure [see Fig. 2(b)] is more complicated. For lower dielectric constant $\varepsilon = 10$, the coupling coefficient even decreases at small

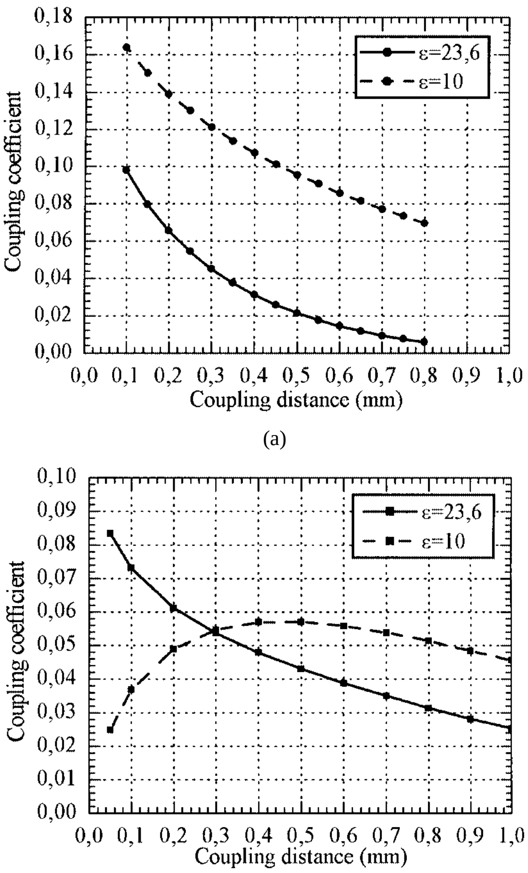

Fig. 2. Full-wave EM simulations of the coupling coefficients as a function of coupling spacing and the dielectric constant (a) for the structure in Fig. 1(a) and (b) for the structure in Fig. 1(b).

coupling distance in comparison with the results obtained for $\varepsilon = 23.6$. This phenomenon may be explained by the cancellation effect for the electrical and magnetic couplings. On the contrary to the first structure, the coupling coefficient of the second pair of the resonators is less sensitive to the variation of the coupling distance and the influence of the dielectric constant is much less pronounced.

Analyzing the results, one may assume that in the structure shown in Fig. 1(a) the coupling is mainly electrical, while in the second structure in Fig. 1(b) the magnetic coupling dominates.

In order to suppress the parasitic cross coupling between nonadjacent resonators, we suggest a filter based on the double-resonator structure with electrical coupling [see Fig. 1(a)] considered as a key constituent. The pairs of resonators are coupled magnetically. Using alternately electrical and magnetic coupling leads to the cancellation effect for cross coupling and improves the frequency response of the filter.

The layout of the 12-pole microstrip filter based on the resonator pairs is shown in Fig. 3. In the filter synthesis, we used the coupling coefficients providing the Chebyshev characteristic. The simulation of the filter performance was carried out by the Sonnet software. The resulting skirt steepness of the filter is the same as that prescribed by the 12-pole Chebyshev prototype (Fig. 4). Using the chosen resonator structure, we avoid widening the filter skirt, though this result is achieved at the cost of a lower rejection level.

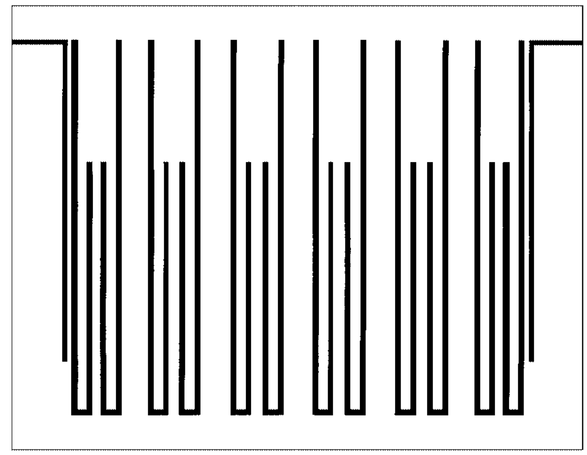

Fig. 3. Layout of the filter.

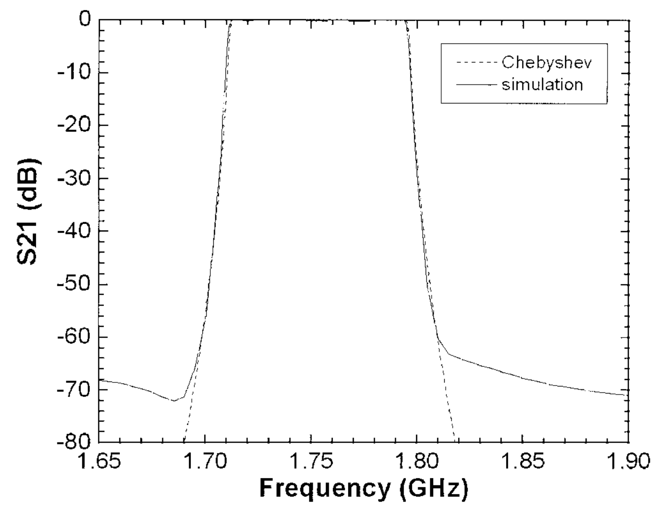

Fig. 4. Simulated performance of the 12-pole filter.

III. Experiment and Discussion

The filter was manufactured on the double-sided HTS YBCO films of 700-nm thickness on an $LaAlO_3$ substrate 0.52 mm thick. The filter area is 17 × 22 mm, which is about $0.37\lambda_{g0}$ by $0.48\lambda_{g0}$, where λ_{g0} is the guided wavelength of the 50-Ω line on the substrate at the midband frequency. The filter was tested in the package with dimensions 30 × 30 × 9 mm. The measured characteristics at $T = 50$ K are presented in Fig. 5 together with the simulation results. There is a very good coincidence between the simulated and measured data. The insertion loss at the midband is about 0.2 dB. The parameters of the YBCO film model [11] and the dielectric constant of the substrate material have been extracted from the preliminary experimental characteristics of the filter at different temperatures. The dielectric constant is 23.6 at $T = 300$ K, and the YBCO film surface impedance can be described by the following model parameters: $\gamma = 2.2$, $\alpha = 10$, $\sigma_n(T_c) = 3 \cdot 10^6$ (Ohm · m)$^{-1}$, and $T_c = 86.5$ K . For extracting the YBCO model parameters, the CAD tool [12] was used.

The filter can be manufactured without trimming, if a set of requirements is fulfilled: 1) the dielectric constant and the thickness of the substrates are the same and 2) the HTS

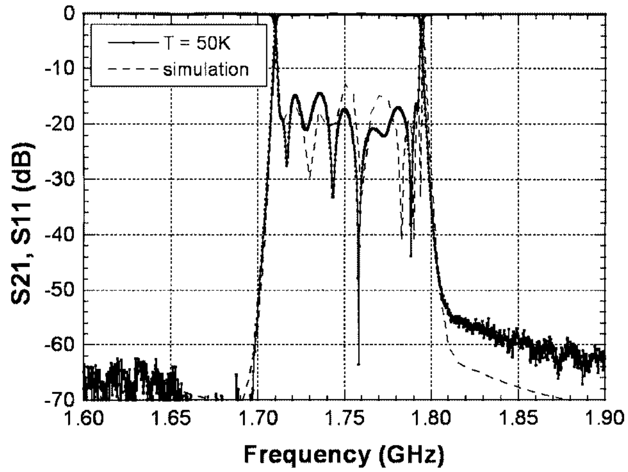

Fig. 5. Measured and simulated performance of the 12-pole filter.

film characteristics (transition temperature and the temperature dependence of the surface resistance) remain unvaried from film deposition to deposition. Becuase of this, the same batch of substrate material should be used and the HTS film deposition conditions should be the same. It may be reasonable to keep these conditions fixed in the case of organization of mass production of the filter.

IV. Conclusion

The HTS planar filter based on the suggested pairs of electrically coupled resonators was designed and measured. Using a combination of electrical coupling inside the pair and magnetic coupling between the pairs of resonators allows us to suppress nondesired couplings between nonadjacent resonators and keep the same steepness of the filter characteristics, which is predicted by the Chebyshev filter prototype of the same order. As follows from Fig. 4, the rejection parameter of the filter is lower as compared with the real Chebyshev characteristics. Thus, the filter can be classified as a pseudo-Chebyshev filter.

The model parameters of the YBCO film were extracted from the experimental filter characteristics measured at different temperatures. The parameters were used for an accurate simulation procedure of the filter and can be further utilized for a simulation of the filters of different structures based on the same YBCO films.

References

[1] G. Tsuzuki, M. Suzuki, and N. Sakakibara, "Superconducting filter for IMT-2000 band," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2000, pp. 669–672.

[2] G. Tsuzuki, S. Ye, and S. Berkowitz, " Ultra selective 22-pole, 10-transmission zero superconducting bandpass filter surpasses 50-pole chebyshev rejection," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 2000, pp. 1963–1966.

[3] S. Kolesov, B. Aminov, H. Chaloupka, T. Kaiser, S. Kreiskott, H. Piel, N. Pupeter, R. Wagner, D. Wehler, H. Medelius, and Z. Draganic, "Cryogenic BTS receiver front end demonstrator," in *Proc. Eur. Microwave Conf.*, vol. 3, 2000, pp. 230–232.

[4] I. B. Vendik, A. N. Deleniv, V. O. Sherman, A. A. Svishchev, V. V. Kondratiev, D. V. Kholodniak, A. V. Lapshin, PN. Yudin, B.-C. Min, Y. H. Choi, and B. Oh, "Narrow-band Y–B–Cu–O filter with quasi-elliptic characteristic," *IEEE Trans. Appl. Superconduct.*, vol. 11, pp. 477–480, Mar. 2001.

[5] D. Zhang, G.-C. Liang, C. F. Shih, Z. H. Lu, and M. E. Johansson, "A 19-pole cellular bandpass filter using 75-mm diameter high-temperature superconducting films," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 405–407, Nov. 1995.

[6] J.-S. Hong, M. J. Lancaster, D. Jedamzik, and R. B. Greed, "On the development of superconducting microstrip filters for mobile communications applications," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1656–1663, Sept. 1999.

[7] G. L. Matthei, N. O. Fenzi, and R. J. Forse, "Hairpin-comb filter for HTS and other narrow-band applications," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 1226–1231, Aug. 1997.

[8] H. T. Kim, B.-C. Min, Y. H. Choi, S.-H. Moon, S.-M. Lee, B. Oh, J.-T. Lee, I. Park, and C.-C. Shin, "A compact narrow-band HTS microstrip filter for PCS applications," *IEEE Trans. Appl. Superconduct.*, vol. 9, pp. 3909–3912, June 1999.

[9] M. Gashinova, I. Kolmakov, Ya. Kolmakov, and A. Deleniv, "Full-wave 3D analysis of boxed microwave planar circuits based on high-Tc superconducting films," in *Abstr. EuCAS*, 2001, pp. 231–232.

[10] J.-S. Hong and M. J. Lancaster, "Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filter," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2099–2109, Nov. 1996.

[11] I. Vendik, "Phenomenological model of the microwave surface impedance of high-T_c superconducting films," *Superconduct. Sci. Technol.*, vol. 13, no. 13, pp. 974–982, 2000.

[12] I. B. Vendik, O. G. Vendik, A. N. Deleniv, V. V. Kondratiev, M. N. Goubina, and D. V. Kholodniak, "Development of CAD tool for a design of microwave planar HTS filters," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 1247–1255, July 2000.

Marina S. Gashinova received the Diploma degree (with honors) in mathematics and mechanics and the B.S. degree in physics from the St. Petersburg Electrotechnical University, St. Petersburg, Russia, in 1991 and 1997, respectively, and is currently working toward the Ph.D. degree at the St. Petersburg State University.

Since December 1999, she has been with the Department of Microelectronics and Radio Engineering, St. Petersburg Electrotechnical University. Her main fields of interest include boundary-value problems in electromagnetic theory, wave propagation through anisotropic media, and filter design. She is currently engaged in the analysis of planar transmission lines embedded in anisotropic materials and multiconductor transmission lines.

Maria N. Goubina was born in Kandalakscha, Russia, in 1974. She received a Diploma (with honors) in radio engineering from the Electrotechnical University, St. Petersburg, Russia, in 1997, and is currently working toward the Ph.D. degree in microelectronics and radio engineering at the Electrotechnical University.

During 1999, she was an Invited Researcher with Wuppertal University, Wuppertal, Germany. Her field of research is modeling superconducting planar components and devices in linear and nonlinear approach.

Dr. Goubina was the recipient of a grant presented by the President of Russia.

Guoyong Zhang received the B.S. degree in physics from Nankai University, Tianjin, R.O.C., and the M.S. degree in physics from Tsinghua University, Tsinghua, R.O.C.

He is currently with Department of Electronics and Electrical Engineering, University of Birmingham, Birmingham, U.K. His field of research interests is in designing microwave filters.

Igor A. Kolmakov was born in Abakan, Russia, in 1978. He received the M.S. degree (with honors) in radio engineering from the St. Petersburg Electrotechnical University, St. Petersburg, Russia, in 2002, and is currently working toward the Ph.D. degree in microelectronics and radio engineering at the St. Petersburg Electrotechnical University.

His research interests are electromagnetic modeling of planar passive device and development of numerical methods.

Yaroslav A. Kolmakov was born in Abakan, Russia, in 1978. He received the M.S. degree in radio engineering from the St. Petersburg Electrotechnical University, St. Petersburg, Russia, in 2002, and is currently working toward the Ph.D. degree in microelectronics and radio engineering at the St. Petersburg Electrotechnical University.

His research interests is designing microwave filters and microwave filter synthesis of theory.

Irina B. Vendik (M'96) received the Electronics Engineer Diploma and Candidate of Sc. (Ph.D.) degree from the Leningrad Electrical Engineering Institute (now St. Petersburg Electrotechnical University), St. Petersburg, Russia, in 1959 and 1964, respectively, and the D.Sc. (Phys.) degree from the A. F. Ioffe Physicotechnical Institute, St. Petersburg, Russia, in 1990.

She is currently a Professor with the Department of Microelectronics and Radio Engineering and Head of the Microwave Computer-Aided Design Group, St. Petersburg Electrotechnical University. Her general research interest have been in foundations of solid-state physics and microwave electronics including low-dimensional crystals at microwave, p-i-n diode switches and phase shifters, and microwave applications of HTSs. Her current activity is in the area of elaboration of HTS microwave components including resonators, filters, power dividers, switches, and phase shifters. She is also interested in the development of computer-aided design (CAD)-oriented models of HTS planar components in linear and nonlinear approaches.