On The Performance of HTS Microstrip Quasi-Elliptic Function Filters for Mobile Communications Application

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***Abstract*—The low-loss and high-selective high-temperature superconducting (HTS) bandpass filters can enhance performance of mobile communications systems. In this paper, we summarize a recent progress of novel HTS preselect bandpass filters that have been developed for a European research project. The objective of the project is to construct an HTS-based transceiver for mast-mounted DCS1800 base stations. The HTS preselect receive filters have been designed to have a quasi-elliptic function response in order to provide low insertion loss and very steep rolloff at the filter band edges. The filters cover a 15-MHz sub-band of a receive band, which ranges from 1710 to 1785 MHz. The filters have been fabricated using double-sided YBCO thin films on 0.3-mm-thick MgO or 0.5-mm-thick LAO substrates. The latest experimental results of the filters, including those encapsulated with a low-noise amplifier in an RF module are presented, showing very promising performance. The issues associated with asymmetric frequency response are investigated to improve the filter performance.**

***Index Terms*—Microstrip filters, mobile communications, superconducting filters.**

I. Introduction

The technology and system challenges of next-generation mobile communications have stimulated considerable interest in applications of high-temperature superconducting (HTS) technology [1]–[7]. System benefits to the cellular mobile communications through the application of HTS technology focus on increased sensitivity and selectivity. To gain these benefits, narrow-band HTS receiver bandpass filters are of importance. This has resulted in the research and development of novel types of HTS bandpass filters [8]–[13]. As far as filter characteristics are concerned, the filter with quasi-elliptic function response is more advanced as compared to the Chebyshev response because it is able to achieve the same selectivity with less resonators and, hence, to have a lower insertion loss [9].

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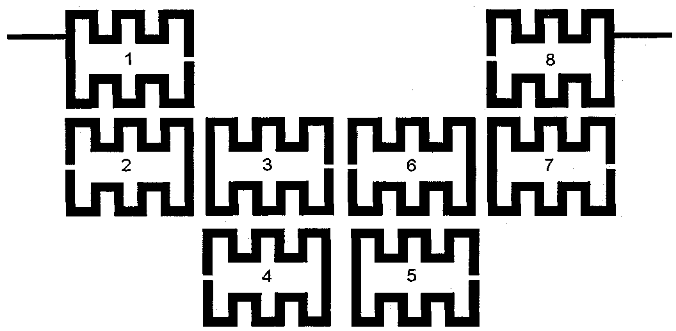


Fig. 1. Eight-pole HTS microstrip filter on MgO substrate with a thickness of 0.3 mm.

In this paper, we summarize the recent progress of novel HTS preselect bandpass filters that have been developed for the European research project "Superconducting Systems for Communications" (SUCOMS). The project is funded through the Advanced Communications Technologies and Services (ACTS) Program. It involved a number of companies (GEC-Marconi, Great Baddow, U.K., Thomson CSF, Orsay, France, and Lybold, Koln, Germany) and two universities (University of Birmingham, Birmingham, U.K. and the University of Wuppertal, Wuppertal, Germany). The objective of the project was to construct an HTS-based transceiver for mast-mounted DCS1800 base stations. The HTS preselect receive filters have been designed to have a quasi-elliptic function response in order to provide low insertion loss and very steep rolloff at the filter band edges. The filters cover a 15-MHz sub-band of a receive band, which ranges from 1710 to 1785 MHz. The filters have been fabricated using double-sided YBCO thin films on MgO or LAO substrates, and have been tested in both liquid nitrogen and vacuum coolers. The filters have been integrated with low-noise amplifiers (LNA's) into an RF module for encapsulation. The development of the filters including the design has been detailed elsewhere [13]. In this paper, we will emphasize the performance of the filters, including the latest experimental and theoretical results.

II. Performance of the Filter on an MgO Substrate

Shown in Fig. 1 is the layout of the developed HTS microstrip filter on an MgO substrate. The filter is comprised of eight mi-

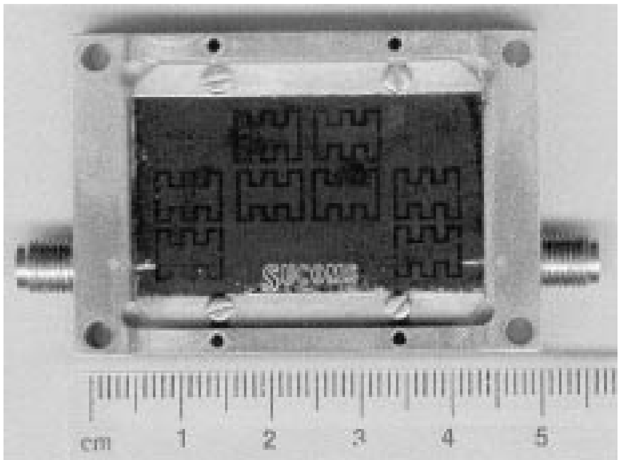


Fig. 2. Fabricated HTS filter in test housing.

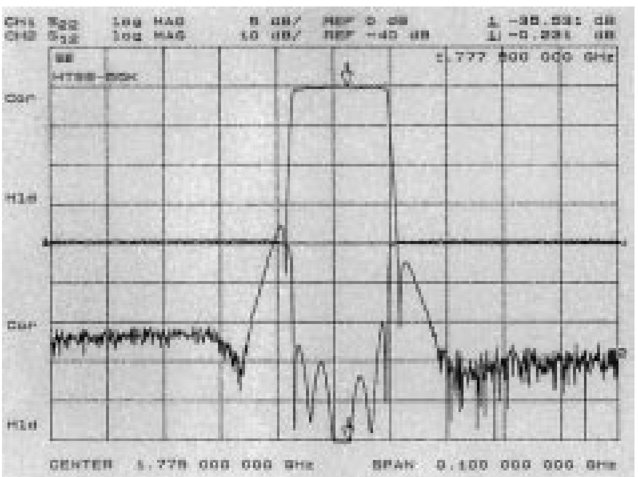


Fig. 3. Measured performance of the HTS filter on an MgO substrate in a test housing at 55 K.

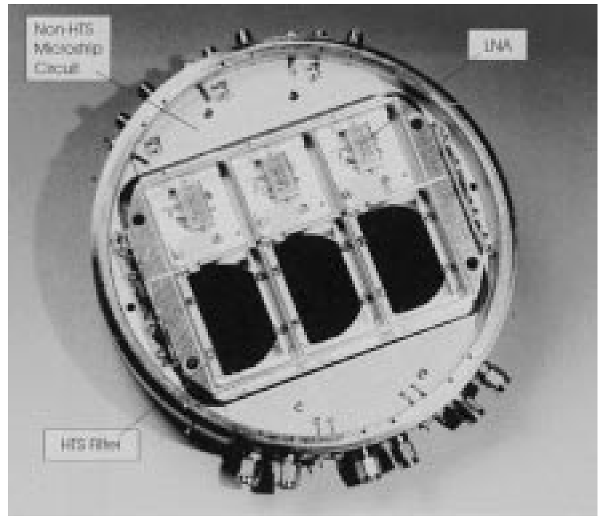


Fig. 4. Three fabricated filters with LAN's in an RF connector ring for encapsulation.

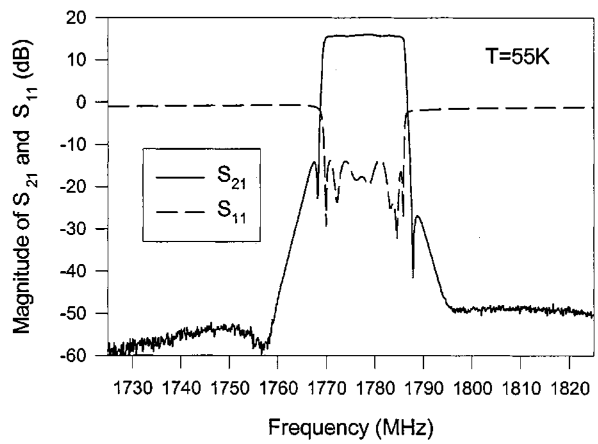


Fig. 5. Measured performance of the encapsulated filter with LNA at 55 K.

crostrip meander open-loop resonators. The attractive features of this filter are not only its small and compact size, but also its capability of allowing a cross coupling to be implemented such that a quasi-elliptic function response can be realized. The numbers indicate the sequence of direct coupling. A single cross coupling between resonators 3 and 6 is desirable in order to realize a pair of attenuation poles at finite frequencies.

The superconducting filter was fabricated using a $YBa_2Cu_3O_7$ thin-film HTS material. This was deposited onto both sides of an MgO substrate that was $0.3 \times 39 \times 22.5$ mm and had a relative dielectric constant of 9.65. Fig. 2 is a photograph of the fabricated HTS bandpass filter assembled inside test housing. The packaged superconducting filter was cooled down to a temperature of 55 K in a vacuum cooler and measured using an HP network analyzer. Excellent performance was measured, as shown in Fig. 3. The filter showed the characteristic of the quasi-elliptical response with two diminishing transmission zeros near the passband edges, improving the selectivity of the filter. It should be mentioned that, to achieve this performance, the tuning is necessary because of a variation in substrate thickness, which has a considerable impact on the performance of narrow-band filters [13].

The major challenges in the applications of HTS to communication systems are not just HTS components alone, but also the associated components in the implementation of the vacuum encapsulation. We have assembled three similarly fabricated filters of the same design with LNA's in an RF connector ring for encapsulation, as shown in Fig. 4. Conventionally, the cryogenic/RF interconnection across the encapsulation vacuum space is accomplished using high-thermal-resistance lossy co-axial cables. In this design, a microstrip feed network and a novel RF/thermal link were used to achieve a low conduction heat load. The RF signals are propagated from the ambient temperature side to the cold side through short thin bondwires. The HTS filters and LNA's in the RF connector ring were cooled down to a temperature of 55 K with an integrated vacuum cooler. The measurements were taken at ports of the RF connector ring. Fig. 5 shows typical measured results of a single channel, while some important measured data are listed in Table I. Again, an excellent performance of the HTS filter after the encapsulation has been obtained. Over the filter passband ranging from 1770

TABLE I
SOME MEASURED DATA OF THE RECEIVE CHANNEL WITH THE HTS FILTER AND LNA

Frequency (MHz)	1768.25	1770	1777.5	1785	1787.5	1805	1825
S_{21} (dB)	–23	15.27	15.85	15.58	–21	–49	–50
S_{11} (dB)		-29.49	-17.69	-20.45			

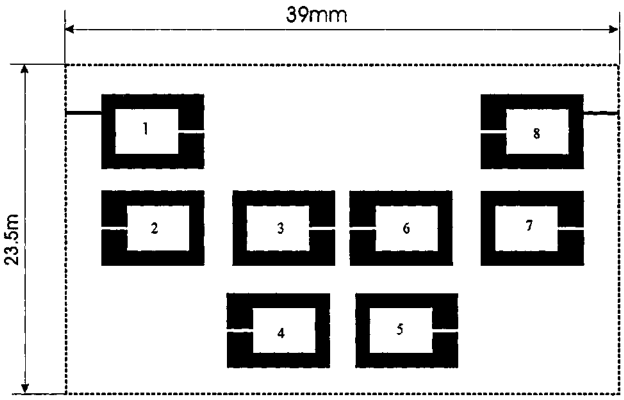


Fig. 6. Layout of the HTS microstrip filter on an LAO substrate with a thickness of 0.5 mm.

to 1785 MHz, the channel had a positive gain around 15.5 dB because of the LNA. A low return loss over the passband was also obtained. High selectivity was achieved due to the two transmission zeros near the passband edges of the filter. At the frequencies of 1768.25 and 1787.5 MHz, which are only 1.75- and 2.5-MHz offset from the low and high passband edges, respectively, the rejection was higher than 36.5 dB. At the nearest transmit frequency of 1805 MHz, the rejection had reached 65 dB. One might notice that the two filter frequency responses in Figs. 3 and 5 are very similar, showing asymmetric locations of the transmission zeros. The asymmetric response is believed due to unwanted couplings that will be addressed latter.

III. PERFORMANCE OF THE FILTER ON LAO SUBSTRATE

Although the excellent performance has been achieved with the HTS filters using MgO substrates, it has been found that the filter performance strongly depends on the uniformity of substrate thickness [13]. To increase the yield and reduce the cost, there is interest in using an $LaAlO_3$ substrate for this type of filter. We have, therefore, designed an HTS filter for fabrication on a 0.5-mm-thick LAO substrate. The design was performed based on the same approach for the filter on the MgO substrate, except for the shape of resonators. Shown in Fig. 6 is the layout of the designed eight-pole HTS bandpass filter comprised of microstrip rectangular open-loop resonators. Similarly, the number presents the sequence of direct coupling, and only one cross coupling, namely, the coupling between resonators 3 and 6 is required for the desired frequency response. The use of the rectangular open-loop resonators instead of the meander ones was intended to reduce the effect of the nonuniformity of substrate thickness. This is because the rectangular open-loop resonator involves fewer discontinuities (right-angle bends) than does the meander open-loop resonator. It has been found that the discontinuities along the open-loop resonator tend to increase the frequency shift due to the nonuniformity of substrate thickness [13]. The filter was fabricated using $YBa_2Cu_3O_7$ thin-film material. This was deposited onto an LAO substrate that is 0.5 $\times$ 23.5 $\times$ 39 mm and has a relative dielectric constant of 23.4. The fabricated filter was mounted in a gold-plated titanium carrier that was assembled into test housing similar to that shown in Fig. 2. Table II summaries the designed performance and parameters versus physical parameters of this filter, where M_{ij} and G_{ij} denote the coupling coefficient and associated coupling gap between resonators i and j. It should be mentioned that the designed performance and parameters are the same as those given for the filters on an MgO substrate.

The packaged filter was first measured with liquid nitrogen in order to tune the filter. After the tuning, the filter was cooled in a cryogenic cooler and measured using an HP8720 network analyzer. Fig. 7(a) plots the measured frequency responses around the passband at 60 K. Although this filter is the first one designed and constructed, it shows a very promising performance. The filter had a passband from 1770 TO 1785 MHz and two transmission zeros near the passband edges as designed. However, there were two extra transmission zeros that occur at the lower and higher stop band, respectively. The frequency response was more asymmetric than that observed with the filter on an MgO substrate. This issue will be addressed in the following section. The wider band response of the filter is shown in Fig. 7(b). One can see that a strong spurious response occurs around 3.5 GHz due to the first higher harmonic of this type of resonator. There are also some minor spurious around 2.7 GHz. This may be attributed to the package. Nevertheless, high rejection is achieved at the desired rejection band from 180 to 1880 MHz.

IV. ASYMMETRIC FREQUENCY RESPONSE

A. Unwanted Cross Couplings

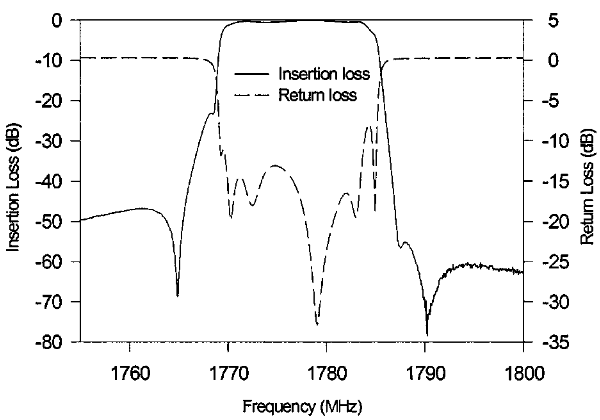
Although the filters developed have shown very promising performance, it is desirable to improve their performance, particularly in regarding the asymmetrical frequency response. Therefore, it is important to identify the causes that distort the symmetrical response. The following are several potential sources which need to be considered:

1) frequency-dependent couplings;
2) discrepancy between the actual and designed couplings;
3) asynchronous resonant frequencies;
4) unwanted couplings.

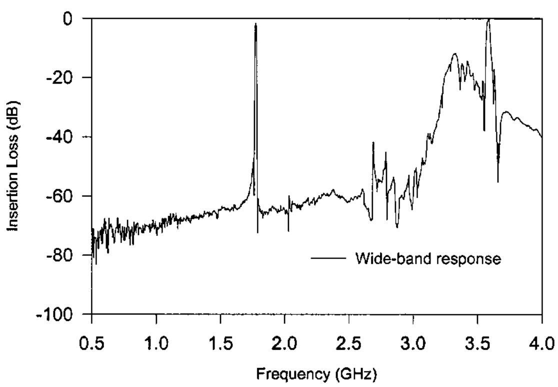
It is true that the frequency-dependent couplings do exist in our distributed-element filter structure. However, for such a narrow-band filter with a fraction bandwidth of less than 1%, it

TABLE II
SUMMARY OF DESIGNED PERFORMANCE AND PARAMETERS VERSUS PHYSICAL PARAMETERS

Designed performance and parameters		Physical parameters	
Centre frequency:	1777.5MHz	Substrate material:	LAO
Passband width:	15MHz	Substrate thickness :	0.5mm
Passband Return loss :	≤ −20dB	Filter pattern dimensions:	39×23.5mm
30-dB rejection bandwidth:	17.5MHz	Housing dimensions:	
Rejection at 1805-1880MHz:	≥ 66dB	39.2×25.6×3.0mm	
Coupling coefficients :	$M_{12}=M_{78}=0.00686$	HTS resonator size:	7.2×5.2mm
	$M_{23}=M_{67}=0.00493$	Coupling gaps (mm) :	$G_{12}=G_{78}=1.588$
	$M_{34}=M_{56}=0.00426$		$G_{23}=G_{67}=2.035$
	$M_{45}=0.00615$		$G_{34}=G_{56}=1.972$
	$M_{36}=-0.00172$		$G_{45}=1.840$
			$G_{36}=1.060$



(a)



(b)

Fig. 7. (a) Measured performance of the HTS filter on an LAO substrate at 60K. (b) Measured spurious response of the filter on an LAO substrate.

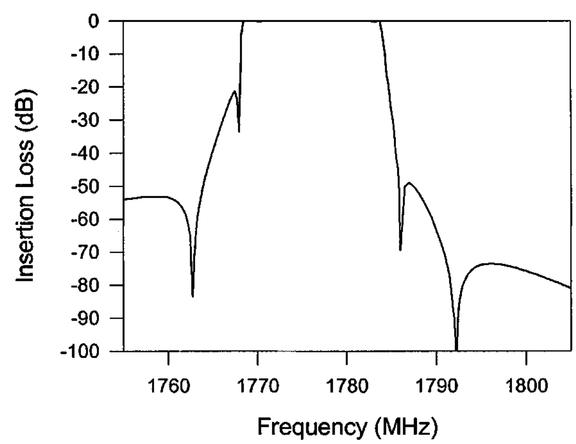
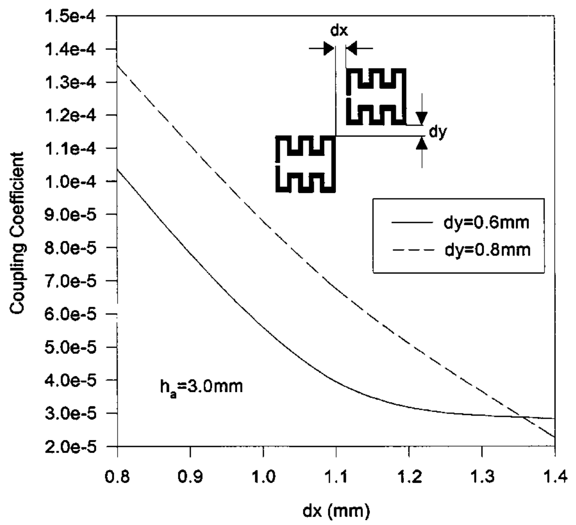


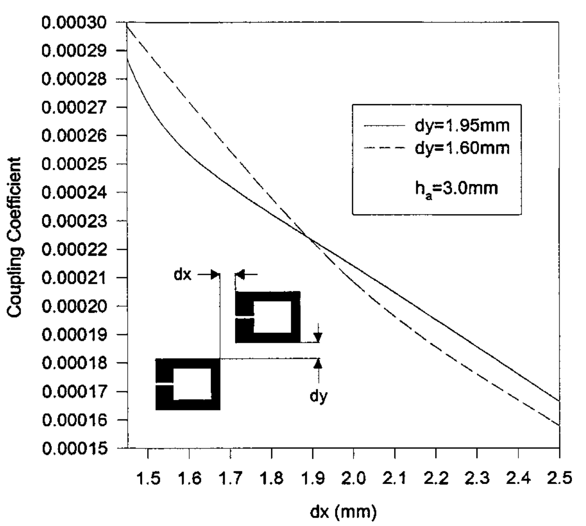
Fig. 8. Full-wave simulated frequency response of the whole filter of Fig. 6.

is unlikely that the effect of the frequency-dependent couplings would distort the frequency response to the extent observed. Fabrication tolerance causes not only the discrepancy between the actual and designed couplings, but also the asynchronous resonant frequencies. In return, this can result in an asymmetrical frequency response. However, the effect is expected to be taken out by the tuning. The full-wave simulation of the whole filter could verify this because it was able to keep the all resonators synchronously tuned and to have symmetric couplings in the simulation. For this purpose, we used a full-wave electromagnetic (EM) simulator [14] to simulate the whole filter of Fig. 6 with a cell size or dimension precision of 0.05 mm. A result of this is depicted in Fig. 8, showing an almost same asymmetric frequency response as that measured in Fig. 7(a).

Therefore, it would seem that the unwanted cross couplings play a key role in the asymmetrical frequency response. Since the microstrip filter is a semiopen structure, any one resonator can couple to the remainders through its fringe field, producing the wanted as well as unwanted couplings. By examining our filter configurations in Figs. 1 and 6, we expect that the unwanted cross couplings resulting from diagonal pairs of resonators, such as resonators 2–4, 3–5, and so on, would be more harmful than the others because of their proximity. Thus, we carried out the EM simulation to characterize these unwanted couplings, and the typical results are shown in Fig. 9. The dimensions of dx and dy chosen for the simulation are in the range corresponding to the fabricated filters, while $h_a = 3.0$ mm is the distance from the HTS thin-film resonator to the housing lid. It has been shown in Table II that the magnitude of wanted couplings for the filters ranges from 0.00172 to 0.00686. From Fig. 9(a), we can see that the magnitude of the unwanted cross



(a)



(b)

Fig. 9. Full-wave simulation of unwanted cross couplings. (a) For the filter on a 0.3-mm-thick MgO substrate. (b) For the filter on a 0.5-mm-thick LAO substrate.

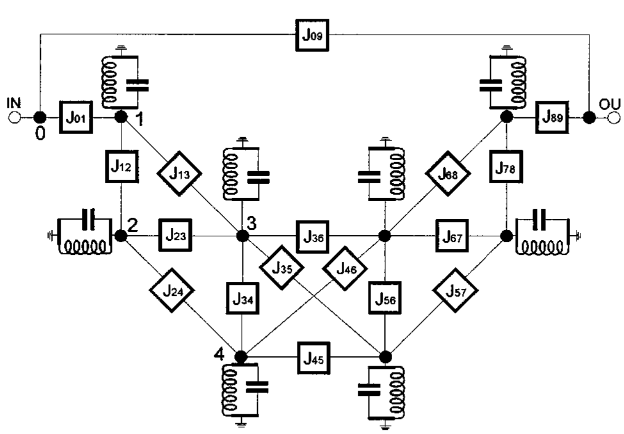


Fig. 10. Circuit model of the filter to take into account the effect of unwanted cross couplings.

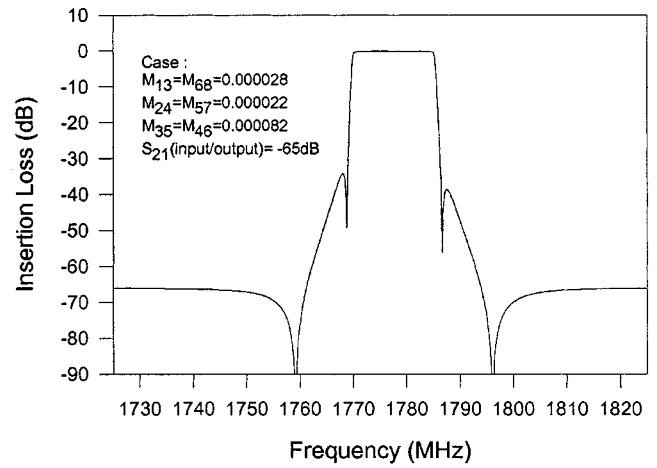


Fig. 11. Predicted frequency response for the filter with the unwanted cross couplings on a 0.3-mm-thick MgO substrate.

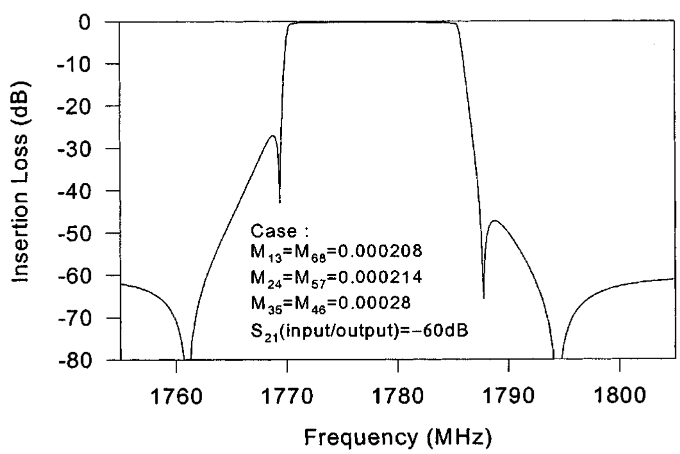


Fig. 12. Predicted frequency response for the filter with the unwanted cross couplings on a 0.5-mm-thick LAO substrate.

couplings for the filter on a 0.3-mm-thick MgO substrate is about 20 times smaller than that of wanted couplings, while Fig. 9(b) shows that the magnitude of the unwanted cross couplings for the filter on a 0.5-mm-thick LAO substrate is only about one order smaller than that of wanted couplings. However, when we substituted the two sets of results for both the filters into a circuit model in Fig. 10, we found that they result in asymmetrical frequency responses that are similar to those measured. It is also found, as expected, that the unwanted crosstalk directly from input to output causes an extra pair of transmission zeros, as we observed. The predicted filter responses in which the simulated unwanted cross couplings and a direct I/O crosstalk are taken into account are plotted in Figs. 11 and 12, showing a fairly good match to the measured responses.

B. Improvement of Symmetric Response

Having identified the main source that caused the asymmetric frequency reposes of the filters, we carried out some investigation on improving asymmetric response. It would be obvious that if the unwanted cross couplings can be reduced, we can obtain better filter response. There are several ways in which

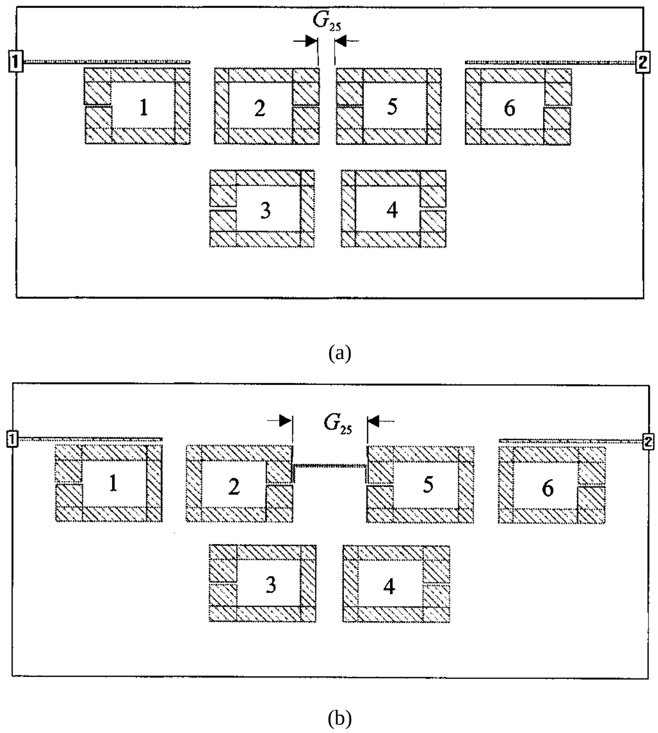


Fig. 13. Two six-pole filter configurations for the full-wave EM simulation. (a) Configuration 1. (b) Configuration 2.

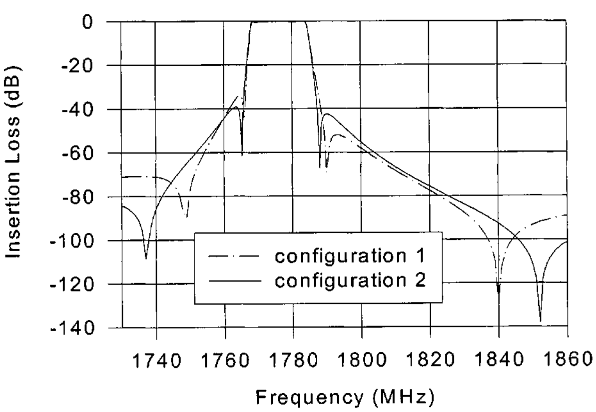


Fig. 14. Full-wave simulated performance of the two six-pole filters in Fig. 13.

the unwanted cross couplings or crosstalks could be reduced. For instance, this may be achieved by using thinner substrate or smaller spacing of h_a between the thin-film resonators and housing lid. However, both ways would degrade the unloaded quality factor of resonators. It may also be possible to inset a thin metal septum into the substrate along the symmetric plane of the filter. The reason why the metal septum needs to be inserted *into* instead of *above* the substrate is because that the unwanted cross couplings can pass through the substrate as well. In this case, the septum may accommodate two apertures that are only for couplings between two pairs of resonators on both sides of the symmetric plane, namely, resonators 4 and 5 and resonators 3 and 6. Obviously, this approach would complicate the filter assembly. Alternatively, it has been found that another effective way to improve the filter symmetric response is to increase the spacing between the pair of cross-coupled resonators.

To validate this approach, we used the full-wave EM simulator [14] to simulate the two six-pole cross-coupled resonator filters in Fig. 13. The filters used the rectangular open-loop resonators similar to those in Fig. 6 on a 0.5-mm-thick LAO substrate with a relative dielectric of 23.4. The all resonators had a similar size of 7.2 $\times$ 5.2 mm for a resonant frequency of 1768 MHz. The two filters were designed to have 15-MHz bandwidth. To realize the required external quality factor $Qe = 119$, the coupled feed line structure with a line width of 0.2 mm was coupled to the I/O resonator through a coupling gap of 0.3 mm. It should be mentioned that the coupled feed line structure could cause a lower resonant frequency of the I/O resonator, which, therefore, should have a slightly small size in order to compensate this effect. The two filters were designed to have the same coupling coefficients $M_{12} = M_{56} = 0.007037$, $M_{23} = M_{45} = 0.004885$, $M_{34} = 0.006016$, and $M_{25} = -0.001368$. For the filter of Fig. 13(a), the coupling gaps entered for the simulation were $G_{12} = G_{56} = 1.70$ mm, $G_{23} = G_{45} = 1.85$ mm, and $G_{34} = 1.85$ mm for the direct couplings. While for the filter of Fig. 13(b), $G_{12} = G_{56} = 1.70$ mm, $G_{23} = G_{45} = 1.55$ mm, and $G_{34} = 1.85$ mm. The main difference between the two filters was the separation between the pair of cross-coupled resonators. This separation has been increased from $G_{25} = 1.15$ mm in Fig. 13(a) to $G_{25} = 5.05$ mm in Fig. 13(b) to reduce the unwanted cross couplings. However, when the separation is increased, the wanted cross coupling will decrease as well. To obtain adequate wanted cross coupling, a transmission line was inserted between the pair of cross-coupled resonators, as shown in Fig. 13(b). Both the filters were simulated in the same box with a size of 43 $\times$ 20 $\times$ 3.5 mm. The cell size used for the simulation was 0.05 mm. This implies that the dimensions of the filters were rounded off to a precision of 0.05 mm. Fig. 14 shows the simulated frequency responses of the two filters. As can be seen, the filter with the configuration of Fig. 13(b) has a much-improved symmetric frequency response.

V. Conclusion

We have reported the recent progress of novel HTS preselect bandpass filters with a quasi-elliptic function response. The filters have been developed for the European SUCOMS Project. We have presented the latest measured performance of the novel HTS filters that have been fabricated using double-sided YBCO thin films on MgO or LAO substrates. Excellent performance of the filters has been demonstrated. The filters have been integrated with LNA's into an RF module for encapsulation. We have identified the effect of unwanted cross coupling as a main source that caused the asymmetric frequency response of the filters. We have suggested and discussed some approaches to improve the filter performance, and have validated an efficient approach by the full-wave EM simulation.

References

[1] D. Jedamzik, R. Menolascino, M. Pizarroso, and B. Salas, "Evaluation of HTS sub-systems for cellular basestations," *IEEE Trans. Appl. Superconduct.*, vol. 9, pp. 4022–4025, June 1999.

[2] STI Inc., "A receiver front end for wireless base stations," *Microwave J.*, vol. 39, no. 4, pp. 116–120, 1996.

[3] S. H. Talisa, M. A. Robertson, B. J. Meler, and J. E. Sluz, "Dynamic range considerations for high-temperature superconducting filter applications to receive front ends," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1997, pp. 997–1000.
[4] R. B. Hammond, "HTS wireless filters: Past, present and future performance," *Microwave J.*, vol. 41, no. 10, pp. 94–107, 1998.
[5] G. Koepf, "Superconductors improve coverage in wireless networks," *Microwave RF*, vol. 37, no. 4, pp. 63–72, Apr. 1998.
[6] Y. Vourc'h, G. Auger, H. J. Chaplopka, and D. Jedamzik, "Architecture of future basestations using high temperature superconductors," in *ACTS Mobile Summit*, Aalbourg, Denmark, Sept. 1997, pp. 802–807.
[7] R. B. Greed, D. C. Voyce, J.-S. Hong, M. J. Lancaster, M. Reppel, H. J. Chaloupka, J. C. Mage, R. Mistry, H. U. Häfner, G. Auger, and W. Rebernak, "An HTS transceiver for third generation mobile communications—European UMTS," in *IEEE MTT-S European Wireless Symp. Dig.*, 1998, pp. 98–103.
[8] 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 film," *IEEE Microwave Guided Wave Lett.*, vol. 5, pp. 405–407, Nov. 1995.
[9] J.-S. Hong, M. J. Lancaster, D. Jedamzik, and R. B. Greed, "8-pole superconducting quasielliptic function filter for mobile communications application," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1998, pp. 367–370.
[10] G. Tsuzuki, M. Suzuki, N. Sakakibara, and Y. Ueno, "Novel superconducting ring filter," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1998, pp. 379–382.
[11] M. Reppel, H. Chaloupka, J. Holland, J.-S. Hong, D. Jedamzik, M. J. Lancaster, J.-C. Mage, and B. Marcilhac, "Sperconducting preselect filters for base transceiver stations," in *ACTS Mobile Commun. Summit*, Rhodes, Greece, June 1998.
[12] E. R. Soares, K. F. Raihn, A. A. Davis, R. L. Alvarez, P. J. Marozick, and G. L. Hey-Shipton, "HTS AMPS-A and AMPS-B filters for cellular receive base stations," *IEEE Trans. Appl. Superconduct.*, vol. 9, pp. 4018–4021, June 1999.
[13] J.-S. Hong, M. J. Lancaster, D. Jedamzik, and R. B. Greed, "On the development of superconducting microstrip filters for mobile communications application," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 1656–1663, Sept. 1999.
[14] *EM User's Manual ver. 2.4*, Sonnet Software Inc., New York, 1993.

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Dr. Lancaster is currently serving on the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium Technical Committee.

Dieter Jedamzik, photograph and biography not available at time of publication.

Robert B. Greed, photograph and biography not available at time of publication.

Jean-Claude Mage (A'85), photograph and biography not available at time of publication.