Transactions of the Materials Research Society of Japan 29[4] 1273-1277 (2004)

Narrowband Superconducting Filters for Mobile Communication

M. V. Jacob, J. Mazierska and A. Knack
Electrical and Computer Engineering, James Cook University, Townsville, Q4811, Australia
Email: Mohan.Jacob@jcu.edu.au

Abstract - Superconducting planar filters exhibit higher selectivity, bigger out-of-band rejection and smaller interference between adjacent channels than metallic planar filters. Using ideas of a modified hairpin, the Chebyshev approximation and cross coupling between non-adjacent resonators, we have designed two HTS filters utilising $YBa_2Cu_3O_{7-\delta}$ thin films on a 58mm×14mm×0.3mm $LaAlO_3$ substrate. A 12-pole superconducting bandpass filter for centre frequency of 1.84 GHz and bandwidth of 5 MHz exhibits simulated passband insertion loss of 0.1 dB and the out-of-band rejection of 50 dB at 1 MHz from the passband. A HTS bandstop filter was designed using the same type of the resonator as the bandpass filter to obtain 50 dB attenuation for the frequency from 1.621 GHz to 1.625 GHz (Iridium satellite).

I. INTRODUCTION

To provide high quality communication services and efficient use of allocated bandwidth highly selective, sensitive and small size filters in their receivers are needed in the mobile radio base stations. Such high performance filters can ensure decrease in adjacent channel interference, better spectrum utilisation, increase in the coverage area without increasing the antenna height, eliminate areas with poor reception or enable a reduction in power requirements of telephone handsets [1].

High selectivity and very low insertion loss require filters with extremely high Q-factors. Air cavity filters exhibit very high Q factor, but their size and weight prevent them from being mounted on towers' top. The small size of filters favours planar circuit technologies, but metallic microstrip filters have high insertion loss due to high surface resistance to be utilised. Hence, conventional filter technologies cannot fulfil conflicting requirements for providing high quality communication services [1].

The most promising applications of High Temperature Superconducting (HTS) materials are passive devices and subsystems for communication technology [2-5] due to very low surface resistance at mobile phone frequencies. HTS planar resonators operating below 2GHz exhibit very high Quality factors and low noise. Incorporation of a Low Noise Amplifier with a superconducting filter inside a cryocooler further creates a cryogenic receiver with reduced Noise Figure [6]. As a result, the radio coverage of a superconducting base station receiver is increased as compared to conventional receivers in rural areas or interference decreased in urban areas resulting in increased revenues for service providers while providing a superior quality of service. In addition to low RF losses, the HTS filters improve the selectivity and the out-of-band rejection of communication receivers. Hence the entire frequency spectrum available for a particular communication provider can be used more efficiently.

The first successful field trials of cellular base station receivers with microstrip superconducting filters started in 1995. Currently, there are already approximately two thousand cryogenic receivers with HTS filters working commercially in base stations in the USA and Asia [7]. Figure 1 shows some of the resonators that have been used to realize superconducting filters. Basic parameters of some filters realised in [5-36] are given in Table I. Most of these filters have been designed using the Chebyshev or Quasi-elliptic approximations.

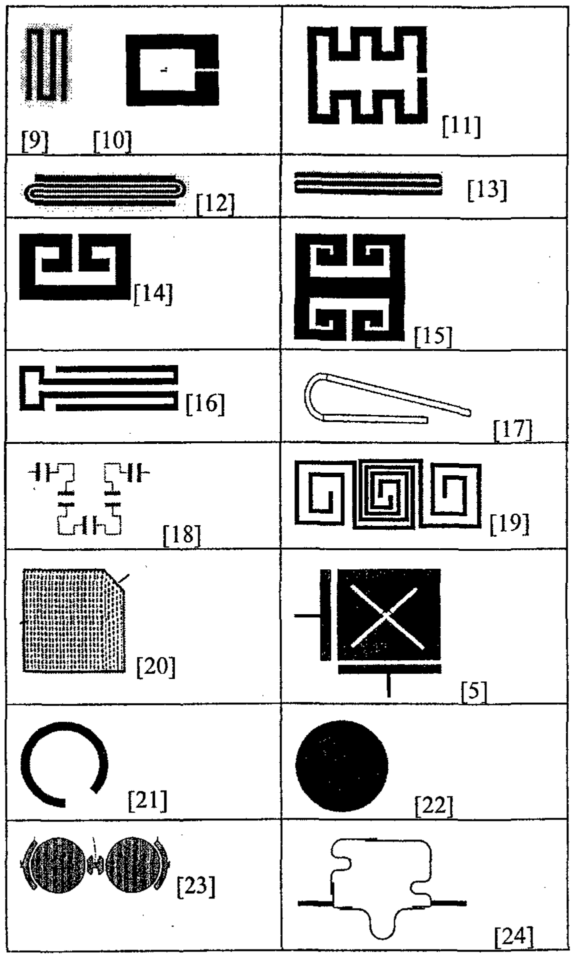

Fig. 1 HTS planar resonators used in filters [1].

For third generation (3G) mobile communication systems it is important to have high out-of band rejection, as allocated bandwidth may be as small as 5MHz. This requires a high number of poles in the filter magnitude function that results in increase of the insertion loss of the filter as well as its surface area. HTS films of large size are expensive and may not be of uniform thickness. Therefore, size minimisation is an important design issue. In this paper we report designs and simulated characteristics of two superconducting filters (bandpass and bandstop) based on the miniaturized hairpin resonator.

II. DESIGN OF THE BANDPASS HTS FILTER

The bandpass HTS filter has been designed for the centre frequency of 1.84 GHz and bandwidth of 5 MHz. A superconducting material (double sided $YBa_2Cu_3O_{7-\delta}$ thin films of thickness 500 nm) deposited on $LaAlO_3$ substrate with ε_r of 24 and thickness 0.3 mm has been chosen. We have used the substrate of 0.3 mm thickness to minimise the radiation loss. The design of the filter has been based on a miniaturised hairpin resonator having coupled lines [34] and nonadjacent coupling [27] and performed using ENSEMBLE, a 2.5D electromagnetic simulator based on the method of moments. This included computations of the length and width of the resonator for the centre frequency 1.84 GHz and evaluation of the coupling coefficients K_{ij} as a function of distance and alignment of two adjacent resonators as in [14].

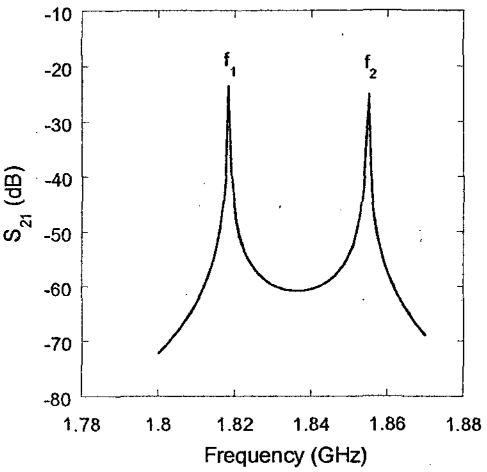

Fig. 2 Simulated frequency response to investigate the coupling coefficient between two adjacent resonators.

An example of a simulated frequency response of two identical resonators separated by a distance d is shown in Fig. 2. The coupling coefficients for four possible resonator arrangements versus separation between them were calculated using the well known equation

$$K = \frac{f_2 - f_1}{\left(\frac{f_2 + f_1}{2}\right)} \tag{1}$$

and are given in Figures 3a-d. Based on the graphs K_{ij} versus d we have designed a compact filter consisting of 12 resonators as shown in Fig. 4 with a bandwidth of 5 MHz.

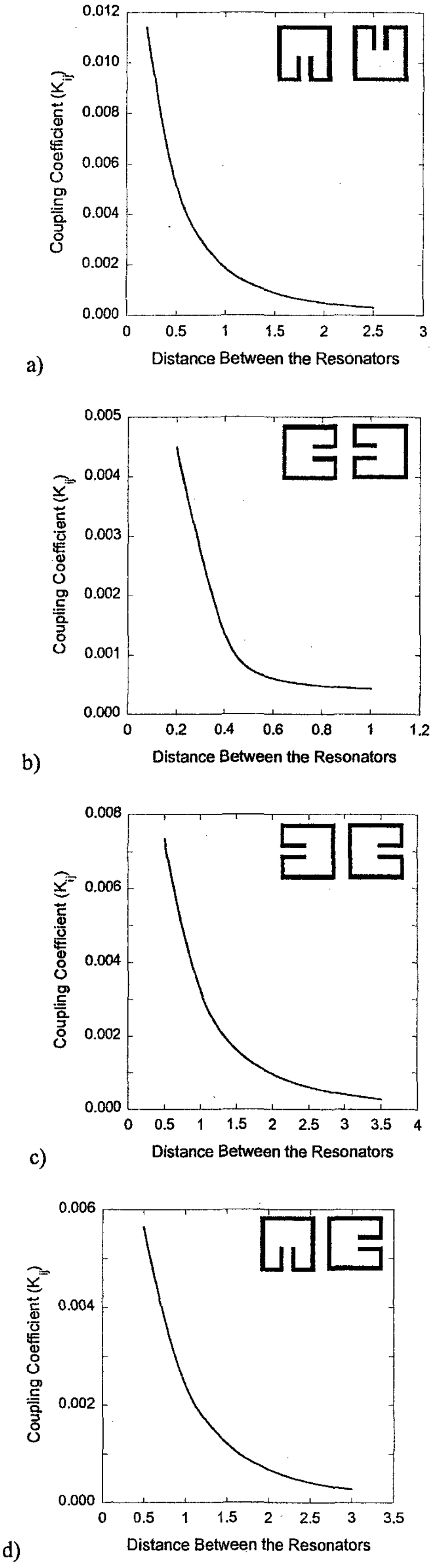

Fig. 3 a-d Computed coupling coefficients versus distance between the resonators for the resonator configurations shown.

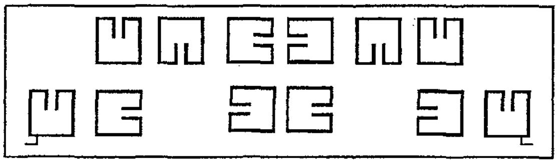

Fig. 4 Layout of the 12 pole bandpass filter

We have used different alignments of the resonators to obtain a small nonadjacent resonator coupling and hence to realise similar responses on the higher and lower frequency side of the passband.

Simulated frequency responses (S_{21} and S_{11}) of the filter of Fig. 4 for the frequency range from 0.5 GHz to 4.5 GHz and from 1.825 GHz to 1.85 GHz are given in Fig. 5a,b. The obtained resonant frequency is at 1.84 GHz and the second harmonic is observed at 3.7 GHz with insertion loss more than 60 dB. The steepness of the skirts of the filter is very good; more than 50 dB at 1 MHz from the passband. The insertion loss is 0.1 dB in the passband and return loss is better than 17 dB for this design. The main advantages of the designed filter are: high number of resonators in the small area, small passband insertion loss and good out of band rejection.

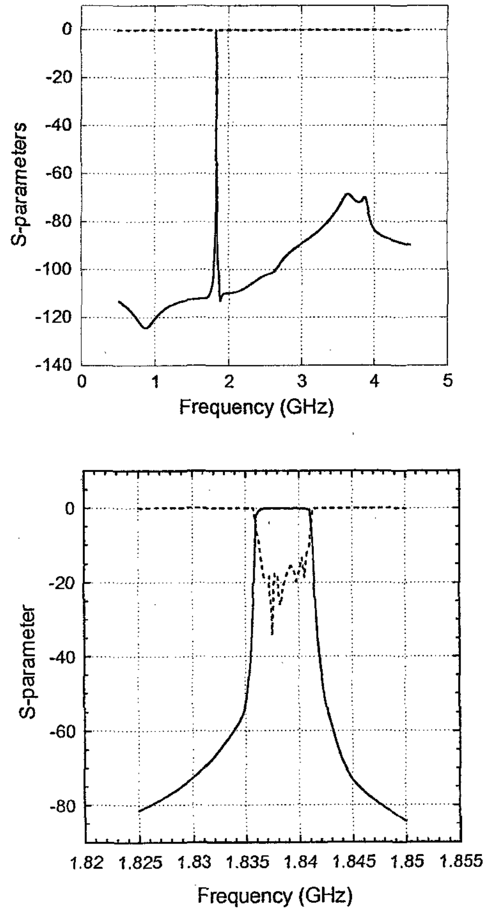

Fig. 5b Simulated S_{21} and S_{11} responses of the filter of Fig. 4 over (a) wide frequency span, (b) narrow span

III. DESIGN OF THE STOPBAND HTS FILTER

A narrow band bandstop filter operating in the frequency range from 1.621 GHz to 1.625 GHz was required to remove signals transmitted by the IRIDIUM system as they interfere with the Australian National Telecopes facilities. We based the filter on the same resonator as discussed in Section II and designed the 8-pole bandstop filter shown in Fig. 6. The filter utilised a double sided $YBa_2Cu_3O_{7-\delta}$ films of thickness 600 nm on $LaAlO_3$ substrate a 0.25 mm thick. The simulated frequency response of the bandstop filter is presented in Fig. 6. The obtained attenuation in the frequency band from 1.621GHz to 1.625GHz is more than 50 dB.

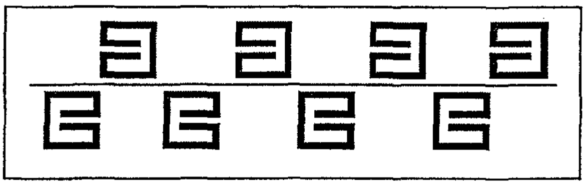

Fig. 6 Layout of Bandstop Filter.

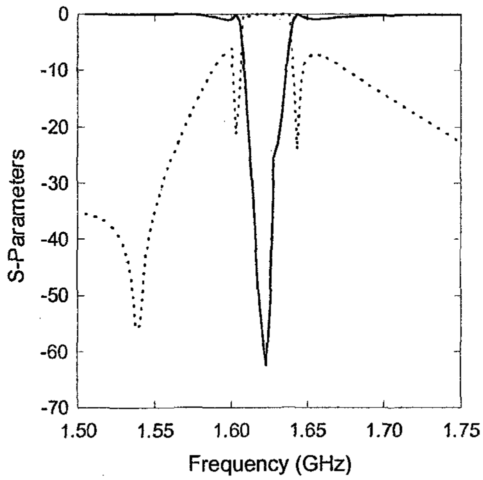

Fig. 7 Simulated S_{21} and S_{11} responses of bandstop filter.

III. CONCLUSIONS

We have designed a bandpass and bandstop superconducting filters characterised by narrow bandwidth using the miniaturised hairpin to achieve small surface area. The bandpass filter was realized using 12 resonators. We have used Chebyshev approximations and cross coupling between the non-adjacent resonators. The centre frequency of the 5 MHz bandwidth filter is at 1.84 GHz and out-of-band rejection is 50 dB at 1 MHz from the passband. The simulated frequency response exhibits a symmetric shape. The effective area of the filter is small (58mm×14 mm) and the influence of the harmonics is not vital. The bandstop filter is designed to prevent the influence of IRIDIUM (1.621-1.625 GHz) and 50 dB attenuation is obtained in the frequency spectrum. The filter is designed on 47 X 11 mm LAO substrate of thickness 0.25 mm.

ACKNOWLEDGEMENTS

ARC Large Grant (799) of James Cook University partly supported this work. MVJ acknowledges the JCU CRIC.

REFERENCES

[1] J. Mazierska and M. Jacob: "High Temperature Superconducting Filters for Wireless Communication", *Novel technologies for microwave and millimeter-wave applications* edited by Jean-Fu Kiang, *Kluwer Academic/Plenum Publishers* 2003.

[2] J. R. Forrest, "Communication Networks for the New Millenium", *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 12, pp.2195-2201, 1999.

[3] C. Gough, "High Temperature superconductors take off", Physics Education, vol. 33(1), pp. 38, 1998.

[4] J. S. Hong, M. J. Lancaster, D. Jedamzik, and R. B. Greed, "On the development of Superconducting Microstrip Filters for Mobile Communications" *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47. pp.1656 – 1663, 1999.

[5] A. Andreone et al., "Development of L-band and C-band superconducting planar filters for wireless systems", *Proceedings of Asia Pacific Microwave Conference* APMC2000, Sydney, pp. 581-586, 2000.

[6] M. Klauda et al. "Superconductors and Cryogenics for future communication systems", *IEEE Transactions on Microwave Theory and Techniques*", vol. 48, No. 7, pp. 1227- 1239, 2000.

[7] S. J. Berkowitz, "Current state of HTS for wireless applications and future needs", *7th Symposium on High Temperature Superconductors in High Frequency Fields*", Woods Hole, MA, June 9-12, 2002.

[8] F. Huang, "Ultra compact superconducting narrow band filter using single and twin spiral resonators, *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, pp. 487-491, 2003.

[9] M. Reppel and J C. Mage, "Superconducting microstrip bandpass filter on LAO with high out of band rejection", *IEEE Microwave and Guided Letters*, vol. 10, No. 5, pp. 180-182, 2000.

[10] J. S. Hong and M. J. Lancaster, "Design of highly selective microstrip bandpass filters with a single pair of attenuation poles at finite frequencies", *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, No. 7, pp. 1098-1107, 2000.

[11] J. S. Hong and M. Lancaster, "Thin film High T_c passive microwave components for advanced communication systems", *IEEE Transactions on Applied Superconductivity*, vol. 9, pp. 3893-3896, 1999.

[12] E. R. Soares, J. D. Fuller, P. J. Marozick and R. L. Alvarez, "Applications of high temperature superconducting filters and cryo-electronics for satellite communication", *IEEE Transactions on Microwave Theory and Techniques*, vol. 48(7), pp. 1190-1197, 2000.

[13] I. B. Vendik et al., "Narrownband YBCO filter with quasi elliptic characteristic", *IEEE Transactions on Applied Superconductivity*, vol. 11, pp. 477-480, 2001.

[14] M. Barra, A. Cassinese, M. Cirillo, M. V. Jacob, R. Russo and R. Vaglio, *"Miniaturized hairpin superconducting filters for telecommunication application"* Journal Microwave and Optical technology letters, vol. 35, pp. 360-362, 2002).

[15] M. Repel and H. Chaloupka, "Novel approach for narrowband superconducting filters", *IEEE MTT-S Digest* 1999, TH2D-6, 1999.

[16] G. Tsuzuki, S. Ye, S. Berkowitz: "Ultra Selective 22-Pole, 10-Transmission Zero Superconducting Bandpass Filter Supasses 50-Pole Chebyshev Filter" 2002 *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, pp. 1963 –1966, 2002.

[17] G. Tsuzuki,, M. Suzuki and N. Sakakibara, "Superconducting filter for IMT-2000 band", *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, No. 12, pp. 2519-2525, 2000.

[18] B. C. Min, Y. H. Choi, S. K. Kim and B. Oh, "Cross coupled band pass filter using HTS microstrip resonators", *IEEE Transactions on Applied Superconductivity*, vol. 11, No. 1, pp. 485-488, 2001.

[19] C. K. Ong "HTS bandpass spiral filter", *IEEE Microwave and Guided wave letters*, vol. 9(10), pp. 407-409, 1999.

[20] Z-Y-Shen, "Planar high temperature superconducting filters with backside coupling", *US Patent 5750473*, May 1998.

[21] G. Tsuzuki, M. Suzuki, N. Sakakibara and Y. Ueno, "Narrow Band 2 GHz Superconducting filter", *Proceedings of Asia Pacific Microwave Conference APMC'98*, Yokohama, Japan, pp. 1509-1512, 1998.

[22] K. Setsune and A. Enokihara, "Elliptic disc filters of HTS films for power handling capacity over 100 W", *IEEE Transactions on Microwave Theory and Techniques*, vol. 48, No. 7, pp. 1256-1264, 2000.

[23] Z-Y-Shen, "TM mode high power high temperature superconducting filters", *US Patent 5710105*, January 1998.

[24] H. Kayano, H. Fuke, F. Aiga, Y. Terashima, R. Kato and Y. Suzuki, "2 GHz superconducting bandpass filter with parallel resonators structure", *Proceedings of Asia Pacific Microwave Conference*, APMC2000, Sydney, pp. 592-595, 2000.

[25] June Sik Kwak, Jong Hyun Lee, Jin Pyo Hong, Seok Kil Han, Wan Sun Kim, Kookrin Char, "Narrow Passband High-Temperature Superconducting Filters with Highly Compact Sizes for Personal Communication Service Application" (preparation, 2002).

[26] T. Kasser, IMS 2002, Presentation (private communication) 2002.

[27] J. S. Hong, M. J. Lancaster, D. Jedamzik, R. B. Greed and J. C. Mage, "On the performance of HTS microstrip quasi-elliptic function ....", *IEEE Trans. On MTT*", vol. 48, No. 7, pp. 1240-1246, 2000.

[28] G. H. Shipton, "Superconducting filters for base stations in the USA", *IEEE IMS MTT-S Workshop Notes*, Workshop on High Performance and Emerging Filter Technologies for Wireless, Phoenix, 2001.

[29] M. Barra, A. Cassinese, M. Cirillo, G. Panariello, R. Russo and R. Vaglio, "Superconducting dual mode

dual stage cross slotted filters", *Microwave and Optical Technology letters*, vol 33, pp 389-392, 2002

[30] R. S. Kwok, D. Zhang, Q. Huang, T. S. Kaplan, J. Lu and G. C. Liang, "Superconducting Quasi-lumped element filter on R-plane sapphire", *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, pp. 586-591, 1999.

[31] 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 narrowband HTS microstrip filter for PCS applications", *IEEE Transactions on Applied Superconductivity,* vol. 9, No. 2, pp. 3909-3912, 1999.

[32] B. Lippmeier, M. Sinclair "HTS Microwave Filter for ANTF", CSIRO Australia, private communication, 2001.

[33] H. Kanaya, T. Shinto, K. Yoshida, T. Uchiyama and Z. Wang, "Miniaturised HTS coplanar waveguide bandpass filters with highly packed meaderlines", *IEEE Transactions on Applied Superconductivity,*, vol. 11, pp. 481-484, 2001.

[34] M. Sagawa, K. Takahashi and M. Makimoto, "Miniaturised hairpin resonators filters and their application to receiver front-end MIC's", *IEEE Transactions on Microwave Theory and Techniques*, vol. 37, pp. 1991-1997, 1989.

[35] I. B. Vengik, M. S. Gashinova, M. N. Goubina, Y. A. Kolmakov, I. A. Kolmakov and G. Y. Zhang, "High T_c superconducting planar filters with improved performance" *IEEE Transactions on Applied Superconductivity,*vol. 13, pp. 284-286, 2003.

[36] F. Aiga, H. Fuke, Y. Terashima, M. Yamazaki, H. Kayano and T. Hashimoto, "HTS hairpin microstrip filter on r-cut sapphire substrate", *IEEE Transactions on Applied Superconductivity,*vol. 13, pp. 287-290, 2003.

(Received October 13, 2003; Accepted March 5, 2004)

Table 1: Specifications of some HTS filters [1].

Ref.	Pole	Type	Substrate	Size mm	f_0	BW	IL	OBR
[5]	2	Chebyshev	LAO	10x10	3.7	1 &10%		30 dB/ 45MHz
[5]	7	Chebyshev	LAO	50"	1.76	75		30 dB/ 5 MHz
[6]	9	Elliptic	Sapphire		1.93	20	0.1	15 dB/MHz
[8]	6	Chebyshev	LAO	13x2.8 mm	1.75	15	0.3	50dB/10MHz
[9]	8	Quasi elliptic	LAO	39x12	1.8	15	0.3	60 dB/ 5MHz
[15]	9	Quasi-elliptic	LAO	39x22.5	1.777	15	0.25	-
[16]	22	Chebyshev	LAO	2"	1.95	20	0.2	30dB/100kHz
[16]	16	Chebyshev	MgO	Half of 3"	1.93	20	0.14	30 dB/ 1.3 MHz
[16]	32	Chebyshev	MgO	3"	1.93	20	0.32	30 dB/ 0.5 MHz
[22]	4	Chebyshev	LAO	14 mm dia	2.38	24	0.21	30dB/40 MHz
[25]	2	Patch	LAO	30	1.909	9.38	0.77	30 dB/25MHz
[25]	9	Chebyshev	LAO	46x18	1.784	11	0.8	34 dB/1 MHz
[26]	13	Quasi-elliptic			1.95	5		80dB/1 MHz
[26]	17	Quasi-elliptic		22x70	1.93	20		30dB/1 MHz
[27]	8	Quasi-Elliptic	LAO	39x23.5	1.778	15	-	30dB/17.5MHz
[27]	8	Quasi-Elliptic	MgO(0.3)	39x23.5	1.778	15	15.5	36.5 dB/2 MHz
[28]	10	Quasi-Elliptic	MgO	34x18	842	15	0.4	60 dB/2 MHz
[29]	4	Chebyshev	LAO	22.3x10	3.32	1%	0.9	50dB/20MHz
[30]	6	Chebyshev	Sapphire	43x10	1.857	20	0.2	60 dB/ 15 MHz
[31]	11	Chebyshev	LAO	50	1.778	11.5	0.6	80 dB/20 MHz
[32]	8	Quasi-elliptic	LAO	50 mm dia	2.260	68	0.7	55 dB/ 10 MHz
[33]	11	Chebyshev	MgO	10x10	1.92	15	0.1	60dB/20MHz
[35]	12	Quasi-elliptic	LAO	17x22	1.747	7	0.3	60dB//1MHz
[36]	17	Chebyshev	Sapphire	35x50	1.929	21.7	0.17	30dB/1MHz