Ultra-Selective 22-Pole 10-Transmission Zero Superconducting Bandpass Filter Surpasses 50-Pole Chebyshev Filter

Genichi Tsuzuki, *Senior Member, IEEE*, Shen Ye, *Member, IEEE*, and Stuart Berkowitz

***Abstract*—An ultra-selective filter for third-generation (3G) and fourth-generation wireless application is presented. The demonstrated filter consists of 22 resonators and five cross couplings that produce ten transmission zeros. The filter was designed at 1950-MHz center frequency with a 20-MHz bandwidth to meet existing 3G wireless applications. The measured filter data shows excellent selectivity, better than 30-dB/100-kHz skirt slopes, and 90 dB of rejection at 350 kHz from the band edge. This filter performance surpasses the performance of a 50-pole Chebyshev filter. In order to fit a large number of resonators into a limited wafer area, a new compact resonator was developed. The filter was fabricated using a YBCO thin film on a 2-in MgO wafer.**

***Index Terms*—Bandpass filter, cross-coupling, group delay, high-temperature superconductor, transmission zero.**

I. Introduction

HIGH-TEMPERATURE superconductor (HTS) filter systems have been tested in third-generation (3G) wireless base stations. Significant improvements, such as increased coverage area and reduced dropped-call rates, have been reported [1] by a cellular operator. However, higher selectivity filters are still required, due to the tightness of frequency resources and the problem of interference from out-of-band signals. These sharper skirt filters are especially in higher data-rate communications, such as in commercial 3G and in the future fourth-generation (4G) wireless applications.

Several papers have reported progress on higher selectivity HTS filters. A highly selective 32-pole Chebyshev HTS filter has been demonstrated using a 3-in HTS wafer [2]. A cross-coupling technique to produce transmission zeros at the band edge for realizing very sharp rejection slopes has been reported [3], [4]. This technique has been applied to HTS microstrip filters [5], [6].

In this paper, we will demonstrate an ultra-sharp skirt filter that has 22 poles and ten transmission zeros. The performance of the filter is able to surpass the performance of a 50-pole Chebyshev filter, as discussed in Section III. To realize this filter, a quadruplet cross-coupling technique was introduced to produce transmission zeros at the band edges. A new compact resonator was also developed to fit 22 resonators into a limited wafer area. The size of new resonator is about one-half of a conventional hairpin resonator.

Fig. 1. Topology of the proposed clip-form resonator. It resonates at 1950 MHz as a half-wavelength resonator. A size of the resonator is 2.15 mm width × 9.6 mm length and its linewidth is 0.3 mm.

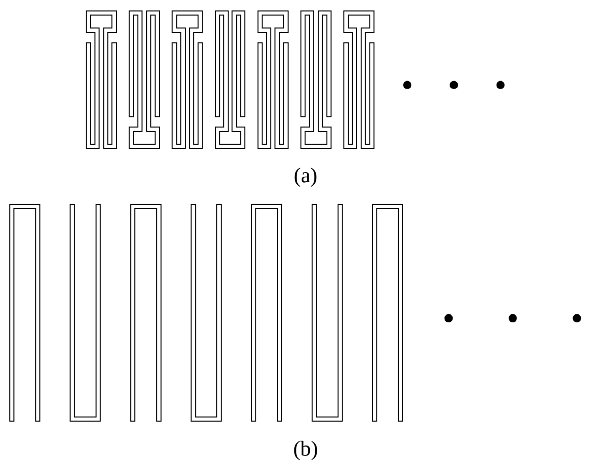


Fig. 2. Resonators' alignment for two kinds of resonators. (a) Clip resonator. (b) Hairpin resonator. Resonators in each topology are aligned in the same separation unit: 3.0 mm for the clip resonator and 4.6 mm for the hairpin resonator. Both topological resonators have the same value of coupling coefficient between adjacent resonators when they aligned in the unit separation.

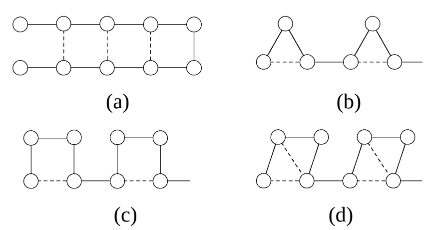


Fig. 3. Several kinds of cross-coupling structures. (a) Canonical structure. (b) Trisection structure. (c) Quadruplet structure. (d) Canonical asymmetric structure. Solid lines denote the main path of coupling and dashed lines denotes cross-coupling.

Manuscript received April 5, 2002; revised August 23, 2002. This work was supported by the National Institute of Standards and Technology, Department of Commerce under the Advanced Technology Program "Advanced Receiver Front-End Technology for 4G Wireless Systems."

The authors are with Conductus Inc., Sunnyvale, CA 94085 USA (e-mail: gen_tsuzuki@ieee.org).

Digital Object Identifier 10.1109/TMTT.2002.805154

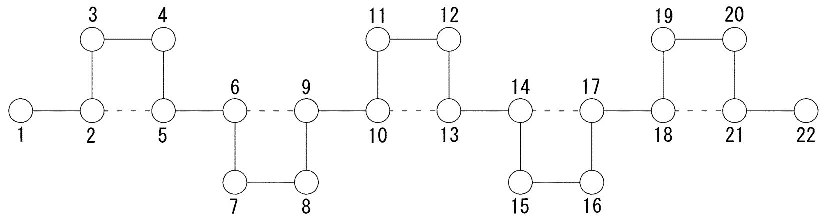


Fig. 4. Diagram of coupling structure of the 22-pole with ten transmission-zero filters. Solid lines denotes the main path and dashed line denotes cross-coupling.

II. Filter Design

A. Resonator

To realize a 22-pole filter in a compact size with low insertion loss, the resonator has to be small and also it has to have a high-Q factor. For that purpose, we used a half-wavelength distributed resonator to achieve a higher Q factor, but the line was folded as a meander to reduce its size.

Fig. 1 shows a new "clip resonator." The resonator has a small loop at the middle of the line, the lines continue down straight in parallel and close each other, and then the lines are folded outward. By aligning the lines of the hairpin in parallel and close to each other, radiation from one resonator to the others can be reduced because the electric current at any two symmetrical positions, with regard to the center of the resonator, flows in opposite directions. Therefore, the electromagnetic field is reduced by the opposite current flow in the parallel lines, hence, the resonators can be placed close to each other.

To fit 22 resonators on a 2-in wafer, not only the resonator itself has to be small, but also the distance between resonators has to be small. Fig. 2(a) and (b) shows alignments of two different kinds of resonators, i.e., for the clip resonator and for a conventional hairpin resonator, respectively. Both resonators have the same linewidth (0.3 mm) and the same resonator width (2.15 mm). The clip resonator is only 9.6 mm long, while the conventional hairpin is 15 mm. The distance between two adjacent resonators (center to center) requires 3 mm for the clip resonator, as opposed to 4.2 mm for the hairpin resonator, in order to realize a typical coupling value of approximately 5×10^{-3} for a 20-MHz bandwidth design in the 3G band. The clip resonator needs only a 28.8 (3 $\times$ 9.6) mm^2 area per one resonator unit, while the conventional hairpin resonator uses a 63 (4.2 $\times$ 15) mm^2 area per one resonator unit. Hence, the clip resonator can reduce the filter size by 54% from the conventional hairpin layout.

It is also very important to reduce the parasitic coupling between nonadjacent resonators to maintain good return loss and rejection slope symmetry. In some cases, this parasitic coupling produces a transmission zero at its band edge [2], which can occur on either side of the filter. Although this effect makes the filter slope steeper, the location of the transmission zero is not controllable. We tried to reduce this unwanted parasitic coupling in order to place the intended transmission zeros at desired locations. The intensity of the major parasitic coupling caused by next-adjacent resonators was calculated to be approximately 2% of the main coupling between adjacent resonators for the clip-resonator case, while the ratio was approximately 5% for the as compared to the hairpin resonator.

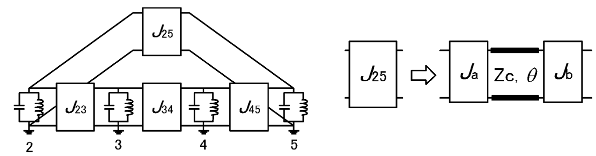


Fig. 5. Equivalent circuit of one of the quadruplet cross-coupling of the 22-pole filter.

B. Coupling Structure

Several kinds of cross-coupling structures have been studied to produce the transmission zeros near the band edge. Fig. 3 shows some typical structures. Cross-coupling structures called canonical structures, as shown in Fig. 3(a), can produce the required transmission zeros, but this approach is too complicated for the design and tuning of such high-order filters. A trisection structure, as shown in Fig. 3(b), has the advantage that each corresponding cross-coupling can control each transmission zero location independently. The quadruplet structure in Fig. 3(c) can produce two transmission zeros at both band edges symmetrically. The locations are adjustable by changing the cross-coupling value. A quadruplet structure can make more transmission zeros using fewer resonators than the trisection structure. A cross-coupling structure called canonical asymmetric block, as shown in Fig. 3(d), had been proposed [7] to produce transmission zeros more effectively. This structure also provides independent adjustment of zero locations, but filter tuning becomes more complicated. The end resonators on each cascaded unit from Fig. 3(b)–(d) can be duplicated to build up higher order filters.

We chose a quadruplet cross-coupling structure for the 22-pole filter in this study. We used this structure to maximize the number of transmission zeros, while keeping a simple cross-coupling structure to design and tune. For this 22-pole filter, the tolerance for each cross-coupling is tight. Since zero locations are very close to the edge, the impact on the filter response from a variation of the cross-coupling value is more serious. The balance between the main coupling, which is the coupling between adjacent resonators, and the cross-coupling is very sensitive for this filter.

The 22-pole filter was designed to meet one of the existing 3G wireless bands; a 1950-MHz center frequency and a 20-MHz bandwidth. Fig. 4 shows the coupling structure for this filter. Five cross-coupling paths were added between the second and fifth, sixth and ninth, tenth and thirteenth, fourteenth and seventeenth, and eighteenth and twenty-first resonators. Fig. 5 shows the equivalent circuit of the first quadruplet cross-coupling block of the 22-pole filter. As shown in Fig. 5,

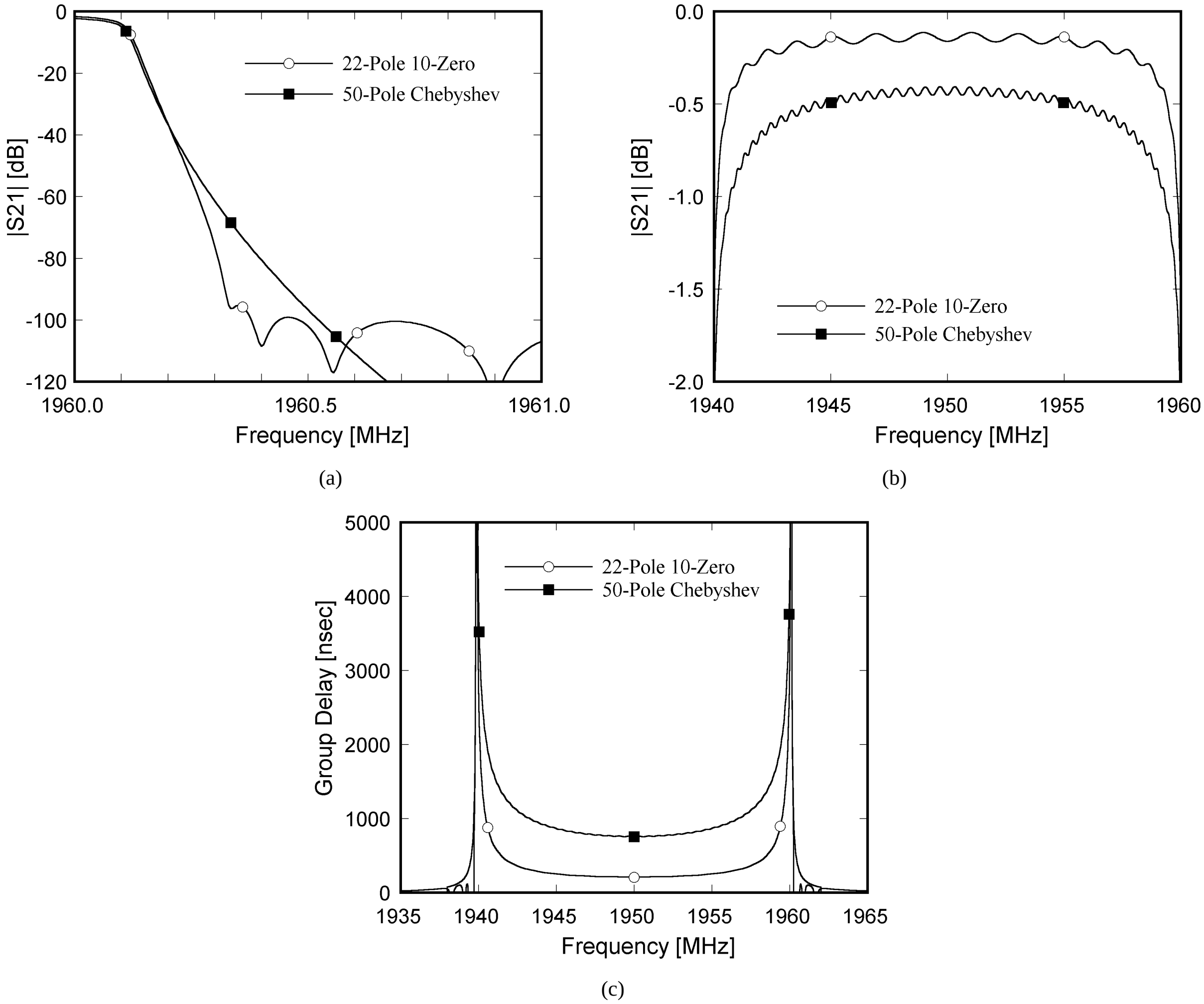


Fig. 6. Comparison of calculated performance between the 22-pole filter and an ideal 50-pole Chebyshev filter. (a) Rejection curves at high sideband edge. (b) Insertion loss curves. (c) Group-delay curves.

the cross-coupling between the second and fifth resonators were made through a transmission line and physical gaps between the transmission line and resonators. The coupling intensity was controlled by J_a and/or J_b. Each cross-coupling produces a pair of transmission zeros at both band edges so that the filter has five transmission zeros at each side of its passband. Five cross couplings were designed to produce zeros located at a distance of 230, 300, 450, 800, and 1600 kHz from both band edges.

III. Comparison With Chebyshev Response

Fig. 6 shows a comparison of the simulated filter performance for a 22-pole resonator with ten transmission-zero design and a 50-pole Chebyshev design. Although the 3G sub-bands have a 20-MHz bandwidth, we designed the filter to have a 20.2-MHz bandwidth. We introduced the 0.2-MHz margin for the bandwidth into the design because the sharp rolloff of the filter leads to a rapid degradation of the insertion loss at the band edge.

In Fig. 6(a), simulated rejection curves at the high sideband edge for two filters are compared. The designed band edge of the filter is at 1960.1 MHz (because of 0.2-MHz margin of bandwidth). The two curves decrease rapidly with the same slope in the region from the band edge to around the 40-dB rejection level. Beyond the 40-dB rejection region, the 22-pole filter maintains the same or even a steeper slope to the 90-dB level because of the five transmission zeros, while the Chebyshev slope becomes more gradual. The frequency points where the rejection achieves 90 dB are at 1960.325 kHz for the 22-pole filter and at 1960.460 MHz for the Chebyshev filter. The 22-pole filter surpasses the 50-pole Chebyshev filter in rejection. The result is the same on the low sideband edge because both responses are symmetrical. For both of designs, the return loss was designed to be the same value.

Simulated insertion loss curves for the two filters are shown in Fig. 6(b). At the band center, the insertion loss is 0.15 dB for the 22-pole filter and 0.45 dB for the Chebyshev design. The curves round off rapidly at the shoulder of the band edges for both cases. The insertion loss at the band edge (1940 and 1960 MHz) is 1.6 dB for the 22-pole and 2.3 dB for the Chebyshev, respectively. In this calculation, the Q factor of the resonator was assumed to be 100 000. The 22-pole filter also surpasses a 50-pole Chebyshev filter with regards to insertion-loss performance.

Fig. 6(c) shows simulated group-delay curves. The 22-pole filter has a wider region where the curve is almost flat near the

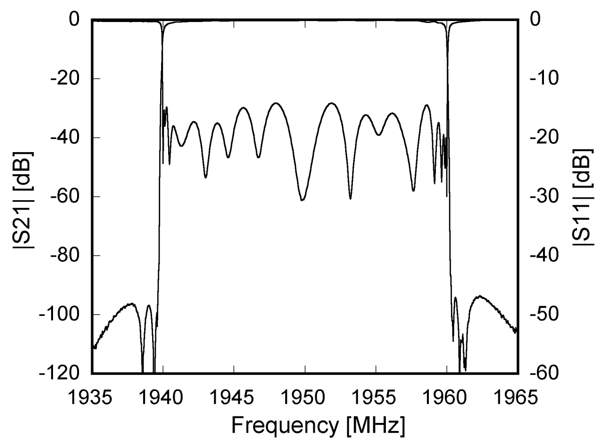


Fig. 7. Measured response of the 22-pole filter at 70 K.

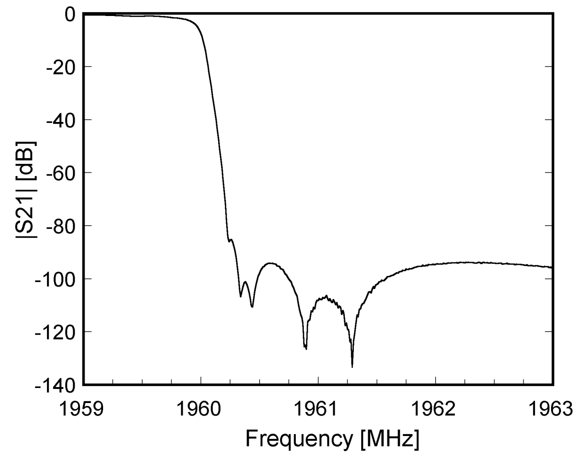


Fig. 8. Measured rejection slope at higher band edge of the 22-pole filter at 70 K.

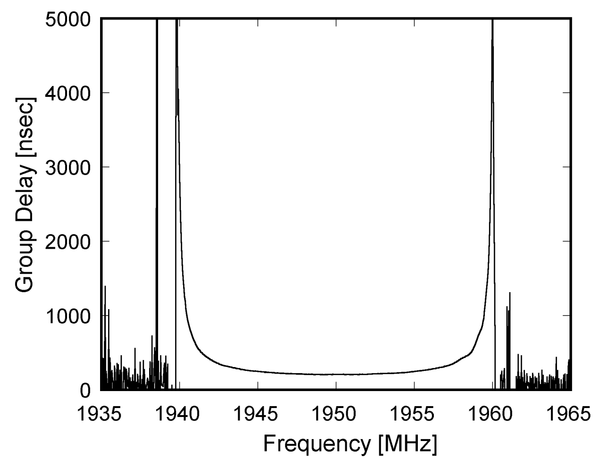


Fig. 9. Measured group delay of the 22-pole filter at 70 K.

center of the passband, roughly 2 MHz inside from both band edges, as compared to the Chebyshev filter design. This is because the 22-pole quasi-elliptic filter has most of the poles distributed around the band edges. Since the group delay increases with pole density, the group delay is low and flat in the middle of the band and high around the edges. The 22-pole filter has ten poles between 1942–1958 MHz, but 12 poles are located outside of the central 16-MHz region. More than half of the poles are located at the band-edge region. On the other hand, 30 poles out of 50 are in the central 16-MHz region for the Chebyshev filter. The rest of the 20 poles, which are 40% of all poles, are located at the band-edge region. This is the reason why the 22-pole filter achieves a flatter curve at the center and becomes sharper at the edge, while the Chebyshev filter has a more rounded curve in the entire passband. The group-delay deviation between the center (1950 MHz) and the peak at the band edge (1960 MHz) is 3000 ns for the 22-pole filter and 5000 ns for the 50-pole Chebyshev filter. The 22-pole filter still surpasses a 50-pole Chebyshev filter with regards to group-delay performance.

Finally, this 22-pole filter also has the advantage of compactness as compared with a 50-pole Chebyshev filter because it needs less than half the number of resonators to achieve better performance.

IV. Measurement

The filter was fabricated on a 2-in YBCO thin-film-coated MgO wafer. Fig. 7 shows the measured filter response at 70 K. Nice brick wall selectivity and return loss was achieved. The insertion loss at the band center was approximately 0.2 dB. The ultimate rejection level exceeded 120 dB, but its real value could not be measured because of the limitations of the network analyzer's dynamic range. Fig. 8 shows the measured rejection performance at the high sideband edge. The input power for the measurements shown in Figs. 7 and 8 was set to $+10$ dBm to make the transmission zeros and bounce back visible. As a result, the insertion loss is more rounded at the shoulder than when measured below 0-dBm input power, where there is no impact on the shoulder. Five transmission zeros can be clearly seen, because the Q factor of the resonator exceeded 100 000. The rejection slope and bounce back agrees well with the simulated curve shown in Fig. 6. Five transmission zeros also appeared clearly at the low side and the slope was quite symmetrical. The rejection points of 90 dB were at 1939.650 MHz (350 kHz from the lower band edge) and 1960.300 MHz (300 kHz from the higher band edge). A rejection slope of over 30 dB/100 kHz was achieved. These numbers agree well with the calculated rejection points of 90 dB at 325 kHz from both band edges. Overall, the measurement is in very good agreement with the design.

Fig. 9 shows the measured group-delay curve for the filter. At the center of the band, the delay was 210 ns, while the peak values at the band edge were 2890 ns at 1940 MHz and 3350 ns at 1960 MHz. The high-side peak was slightly bigger because the higher band edge had less bandwidth margin. This result was consistent with the results of the 90-dB rejection points. This slight imbalance can be adjusted by changing the operating temperature of the cryocooler. This filter has a center frequency shift of approximately 100 kHz/1 K around the 70-K operating temperature. The measured group-delay deviation of approximately 2900 ns for this ultra-selective filter was consistent with the simulated value shown in Fig. 6. The measured value of the group delay at the band center was also consistent with the simulated value of 210 ns.

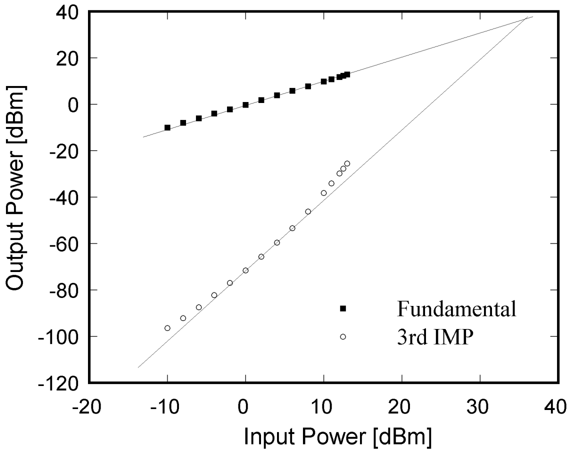


Fig. 10. Two-tone third-order IMP at 70 K. Fundamental signals are located at 1945 and 1950 MHz. IMP appeared at 1955 MHz was measured. The reference lines with slopes 1 and 3 for both fundamental and IMP are drawn, respectively. The intercept point is approximately +36 dBm.

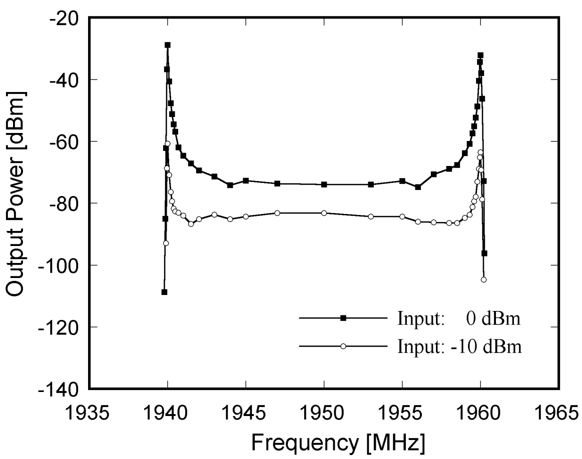


Fig. 11. Frequency dependence of IMP at 70 K. Fundamental two-tone signals separates 30 kHz away each other. Two different input powers, i.e., 0 and 10 dBm, of the two-tone signal are plotted.

The distortion characteristics of the third-order intermodulation product (IMP) for the 22-pole filter were also measured. Fig. 10 shows the IMP at 1955 MHz generated by in-band two-tone fundamental signals, i.e., 1945 and 1950 MHz. The measured IMP curves had a slope of three and the third-order intercept point (IP3) was approximately +36 dBm at 70 K. The frequency dependence of the IMP is plotted in Fig. 11. The two-tone fundamental signals were separated 30 kHz away each other. The IMP peak signal level in the band-edge region was higher than the signal levels around the band center by approximately 20 dBm for −10-dBm input power and approximately 40 dBm for 0-dBm input power.

V. Conclusion

A clip-shape resonator has been proposed to realize both compactness and high-Q factor. The quadruplet cross-coupling technique was introduced to produce ten transmission zeros. With the combination of this new resonator structure and the quadruplet cross-coupling technique, an ultra-sharp rejection slope filter was achieved on a 2-in wafer area. The measured filter's performance surpassed a 50-pole Chebyshev filter, and it has exceeded every rejection performance previously reported, to the authors' knowledge.

On the other hand, the demonstrated 22-pole filter has quite a large group-delay deviation between its peak at the band edge and its bottom at the band center. This is unavoidable since a steeper slope rejection results in a larger group-delay deviation. Although the demonstrated filter would result in quality improvements in high data-rate cellular systems by an extreme reduction of the out-of-band signal noise, its large group delay might impact the quality of demodulation. This issue will be considered in future study.

Acknowledgment

The authors would like to thank J. Danielzadeh, S. Corrales, S. Muniz, and J. Pador, for the filter fabrication, and G. Page, and Q. Thai, all with Conductus Inc., Sunnyvale, CA, for the filter tuning.

References

[1] Y. Amano, T. Inoue, M. Nakanishi, H. Suganami, T. Youkai, T. Suzuki, and G.-C. Liang, "Field trial of IMT-2000 testbed with superconducting filter," in *IEICE Soc. Conf. Dig.*, Sept. 2000, Paper B-5-115, p. 403.

[2] G. Tsuzuki, M. Suzuki, and N. Sakakibara, "Superconducting filter for IMT-2000 band," *IEEE Trans. Microwave Theory Tech.*, vol. 48, pp. 2519–2525, Dec. 2000.

[3] A. E. Atia and A. E. William, "Narrow bandpass waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 258–265, Apr. 1972.

[4] R. J. Cameron and J. D. Rhode, "Asymmetric realization for dual-mode bandpass filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 51–58, Jan. 1981.

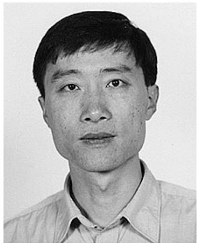
[5] J. F. Liang, C. F. Shin, Q. Huang, D. Zhang, and G. C. Liang, "HTS microstrip filters with multiple symmetric and asymmetric prescribed transmission zeros," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 4, June 1999, pp. 1551–1554.

[6] K. F. Raihn, R. Alvarez, J. Costa, and G. L. Hey-Shipton, "Highly selective HTS band pass filter with multiple resonator cross-couplings," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, June 2000, pp. 661–664.

[7] J. F. Liang and D. Zhang, "General coupled resonator filters design based on canonical Asymmetric building blocks," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, June 1999, pp. 907–910.

Genichi Tsuzuki (M'95–SM'02) received the B.Sc., M.Sc., and Ph.D. degrees from Kanazawa University, Kanazawa, Japan, in 1987, 1989, and 1992, respectively, all in theoretical physics. His doctoral research focused on the study of quantum fluctuation phenomena as related to phase transition states such as superconductivity and charge density wave and spin density wave in low-dimensional crystal structure.

From 1992 to 1994, he was with the DENSO Corporation, Kariya, Japan, during which time he was involved with semiconductor devices research and development. From 1994 to 1999, he was with Advanced Mobile Telecommunication Technology Inc. (AMTEL), Nisshin, Japan, where he was involved in research and development of several HTS filter projects. From 1999 to 2000, he was with Cryodevice Inc., NIsshin, Japan, where he led several HTS RF front-end subsystem projects that include the development of HTS filters, low-noise amplifiers, cryogenic isolators, and cryo-coolers for wireless applications. In 2000, he joined Conductus Inc., Sunnyvale, CA, where he has been involved with several research projects in both commercial application and under government contract for innovative HTS filter subsystems. His current research interest includes analytical and numerical techniques for microwave passive circuits and application of HTS technology to high-power transmit filters.



Shen Ye (S'88–M'91) was born in Shanghai, China. He received the B.Eng. and M.Eng. degrees from Shanghai University (formally the Shanghai University of Technology), Shanghai, China, in 1982 and 1984, respectively, and the Ph.D. degree from McMaster University, Hamilton, ON, Canada, in 1991, all in electrical engineering.

From 1984 to 1986, he was an Assistant Lecturer with the Department of Electrical Engineering, Shanghai University of Technology. In 1991, he joined Optimization Systems Associates Inc., Dundas, ON, Canada. He implemented microstrip components for a computer-aided design (CAD) package. He developed Empipe, which connects an electromagnetic field solver to the CAD package. In 1993, he joined COM DEV International, Cambridge, ON, Canada, where he was a Principle Member of Technical Staff. His contributions include designs of HTS thin-film filters, multiplexers, and high-power HTS thin-film filters. He developed various application-specific CAD programs, in particular, an advanced computer-aided tuning software package. In March 2000, he joined Conductus Inc., Sunnyvale, CA, where he has been involved with the design and commercialization of ultrahigh performance HTS thin-film filters for cellular and 3G base-station applications.

Dr. Ye was the recipient of a 1991 Industrial Research Fellowship presented by the Natural Sciences and Engineering Research Council of Canada

Stuart Berkowitz was born in 1966. He received the B.S. degree in physics from North Carolina State University, Raleigh, in 1988, and the Ph.D. degree in physics from Boston University, Boston, MA, in 1993.

Since 1993, he has been with Conductus Inc., Sunnyvale, CA, where he is currently the Manager of the RF Development Group for Government Systems. He has coauthored over 20 papers. He holds one patent.

Dr. Berkowitz has presented several invited talks at international conferences on superconductivity and RF applications.