Design of 5-Channel C-Band Input Multiplexer for Communication Satellites

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***Abstract*—In a multi user communication environment such as communication satellites, inter-channel isolation is provided by channelizing/multiplexing networks that splits composite wideband signal into various narrowband RF signals corresponding to each user. In a communication satellite transponder, input multiplexing network is placed at the output of low noise receiver. It divides the composite received signal into various narrowband signals and controls the interference among the channels below certain level. The stringent isolation requirements of these networks require the channel filters to have transmission zeros to be placed just outside the passband. This paper describes the electrical design of a 5-channels C-band input multiplexer (IMUX). Comparative analysis of different multiplexer configurations is described in detail. Among different available filter technologies for realization, dual mode circular waveguide technology is an optimum choice. In order to meet the in-band performance requirements, 10th order channel filters were realized with four transmission zeros for stopband rejection and four transmission zeros for group delay equalization (10-4-4). System-level simulation of of the multiplexer is performed and the simulation show good agreement with design requirements.**

I. INTRODUCTION

In communication satellites, a single antenna receives the uplink channel group which needs to be separated to before amplification stage [1] to maintain certain level of isolation among the channels. A generic transponder of communication satellite is shown in Fig. 1. The division into channels and subsequent recombination of these is done by input and output multiplexing networks respectively which are composed of narrowband bandpass filters with fraction bandwidth of 0.2~2% [2]‒[3]. The input multiplexer (IMUX) comprises of an assembly of quite complex filters which separate the closely packed channels without introducing appreciable signal distortion [4].

The most critical electrical parameters for the channel filters are passband insertion loss variations, group delay and stopband attenuation. The absolute insertion loss is less critical than insertion loss variations as IMUX lies before the amplification stage of the transponder and after the LNA [14]. The physical parameters for IMUX such as layout, mass and volume are sometimes of critical importance as the mass of electronic equipment significantly contributes towards the overall cost of the spacecraft [8].

In this paper, the design of 5-channels C-band input multiplexer is presented. The multiplexer is based on the channel-dropping topology in which channel filters are connected by circulators and isolators. The circulator is part of the multiplexer function and used for channel dropping, while the isolator is inserted at the output to isolate the filter from any mismatch [8]. The circulators are non-reciprocal 3-port devices, made from ferrite material, which allow the unidirectional flow of energy [14].

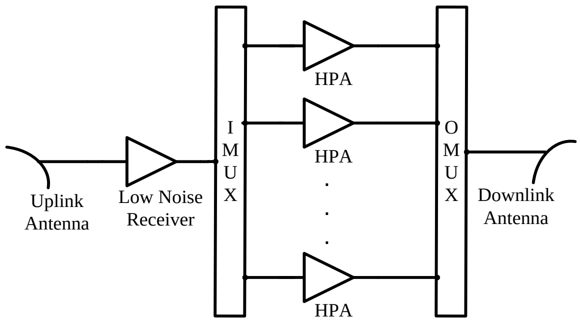


Fig. 1. Simplified block diagram of payload of communication satellite. [14]

TABLE I.
FREQUENCY PLAN OF C−BAND INPUT MULTIPLEXER

Channel	Center Frequency (GHz)	Bandwidth (MHz)
1	3.72	36
3	3.8	36
5	3.88	36
7	3.96	36
9	4.04	36

Section II describes the most commonly used multiplexer configurations. In Section III a comparison of various technologies used to design microwave filters are given, and Section IV deals with the design of channel filters. In the end, the system level simulation of IMUX is discussed in Section V.

II. MULTIPLEXER CONFIGURATIONS

The frequency plan and key performance specifications of input multiplexer are given in Table I and Table II respectively. For the electrical design of the input multiplexer, the first step is the selection of a best topology of multiplexer from the available ones. For the selection of topology; many parameters like layout considerations, design complexity, modularity in design, technology limitations and industrial practices are kept in mind. The most commonly used configurations are hybrid-coupled multiplexers, circulator-coupled multiplexers, and manifold-coupled multiplexers. [1]

A. Hybrid Branching Multiplexer

In this configuration, the wideband composite signal is divided into two equal paths by the means of 3 dB hybrid until the number of paths equals the number of channels.

TABLE II.
KEY SPECIFICATIONS OF CHANNEL FILTERS

Property Name	Frequency	Specification
Insertion Loss Flatness (dB)	f_0±10 MHz f_0±16 MHz f_0±18 MHz	≤ 0.3 ≤ 0.6 ≤ 1.1
Insertion Loss Slope (dB/MHz)	f_0±10 MHz f_0±16 MHz f_0±18 MHz	≤ 0.1 ≤ 0.5 ≤ 0.6
Group delay (ns)	f_0±10 MHz f_0±16 MHz f_0±18 MHz	≤ 3 ≤ 20 ≤ 42
Out-of-band Rejection (dB)	f_0±22 MHz f_0±50 MHz	≥ 14 ≥ 48

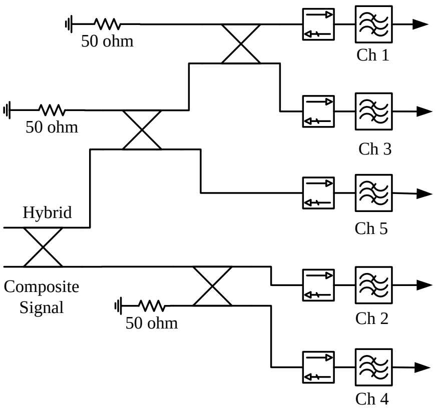


Fig. 2. Layout of 5-channel hybrid-branching multiplexer.

Channel filters are placed at the end of each path with an isolator at its input. In Fig. 2, a typical 5-channels input multiplexer based on this configuration is illustrated. The advantage of this topology is that filter design is relaxed and the interaction among the channels is very small but at the cost of higher insertion loss. A typical hybrid corresponds to around 3.5 dB insertion loss.

B. *Circulator Coupled Multiplexer*

Also known as the *channel-dropping* technique [4], illustrated in Fig. 3. The hybrid at the input divides the signals into two branches. The circulator located at the beginning of each branch, directs the composite signal to the input of first filter in the branch. This filter allows the signal corresponding to its passband and remaining channels which in the stopband region of the filters are reflected. The reflected signal is directed towards next circulator/channel filter and so on, until all the remaining channels are terminated in the load at the end of the chain.

The configuration utilizes all the advantages of hybrid branching topology with much lower insertion loss. Owing to the large frequency gap among the nonadjacent channels of each branch, the degradation due to reflections of channels is minimal.

C. *Manifold coupled Multiplexer*

Manifold coupled multiplexers are used where size and absolute insertion loss requirements are very critical. In this approach the channel filters are placed on a manifold, which is a long waveguide, and the inter-channel interactions are compensated during the multiplexer

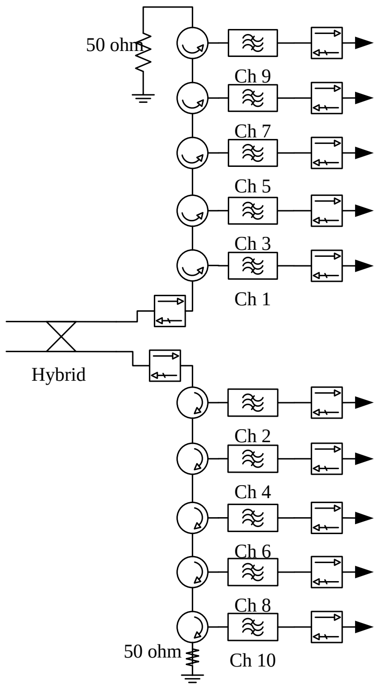


Fig. 3. Layout of 10-channel circulator-coupled multiplexer.

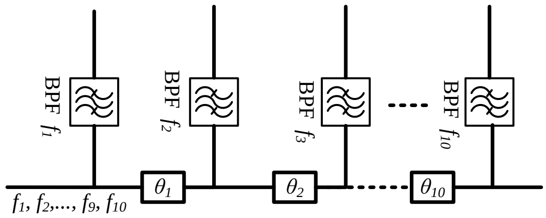


Fig. 4. Layout of 10-channel manifold-coupled multiplexer.

design, usually by optimization. This approach is not amenable to change in frequency plan and implementation of multiplexer becomes more difficult as the number of channels increases. Any change in the channel filter specifications requires a new multiplexer design. The multiplexer based on this configuration is shown in Fig. 4.

D. *Selection of IMUX Configuration*

The advantages and disadvantages of each topology are presented in Table III. The circulator coupled IMUX topology is found to be most suitable for having low loss simple layout, easy to tune and amenable to modular concept. This topology is also the most widely used in the space industry [5], [6] and [23]. Since the circulators and isolators being compact in size have relatively higher loss nearly 0.3 dB, so this scheme requires channel filters to have high unloaded Q [14].

III. SELECTION OF CHANNEL FILTER TECHNOLOGY

While selecting the technology for the realization of channel filters; the main focus is the mass requirement, available unloaded Q of the resonators, design complexity, spurious free-window, reliability, post-manufacturing tuning range, and heritage of the design. There are many filter technologies that can be used to design IMUX, namely, coaxial filters, waveguide filters, dielectric resonator filters, and pre-distorted filters.

From Table III it is evident that circular waveguide filter is the one that can meet the requirements of low insertion loss with the size and mass in available limits. Also these filters have been widely used in space industry [6]. The dual mode circular waveguide technology was selected for the design of channel filters on the basis of spurious free window, design complexity, post-manufacturing tuning capability and high unloaded Q.

IV. Design of Channel Filters

Traditionally, the design of waveguide filters is based on divide-and-conquer strategy [12] and the design process can be divided into a number of steps; starting with determination of filter order and lowpass prototype filter function meeting all the requirements. A recursive process [13] is used for the generation of generalized Chebyshev filtering function polynomial. Once the filter polynomial satisfying all the specification requirements of out-of-band rejection, insertion loss flatness, and group delay response etc. have been produced. The lowpass prototype filter circuit may be modeled in the form of coupling matrix. Each element of coupling matrix corresponds to an element in the final filter structure [14]−[19].

Temperate variations cause the volumetric thermal expansion of the filter structure and the equivalent linear frequency drift is incorporated at the synthesis stage of the filter. The overall temperature drift of the filter depends upon the thermal coefficient of the resonance cavity and tuning screws [6]. The drift in terms of frequency due to thermal variation is related by

Temperature drift = $f_0 \Delta T \tau$

where f_0 is center frequency, ΔT is operating temperature range and τ is thermal expansion coefficient of the material. For *invar* material the frequency due to drift is 0.6 MHz when the operating temperature range is 50°C.

Dual mode cylindrical waveguide filters are based on polarized mode degeneracy within the same cavity and can realize negative couplings without capacitive probes [14]. Both transverse electric (TE) and transverse magnetic (TM) modes can be degenerate, and dual TE_{11n} mode in cylindrical cavities is used most often [21]−[22].

TABLE III.
Comparison of IMUX Configuration

	Hybrid Branching IMUX	Circulator Coupled IMUX	Manifold Coupled IMUX
Advantages	Amenable to modular concept	Amenable to modular concept	Most Compact Design
	Simple to tune ,no interaction between channel filters	Simple to tune, minimum interaction between channel filters	Capable of realizing minimum insertion loss than other topologies.
	Requires one filter per channel	Requires one filter per channel	Requires one filter per channel
Disadvantages	Physical size and mass is greater than any other topology	Signal must pass in succession through circulators	Complex Design
	More loss than any other topology	More loss than Manifold coupled MUX but less than Hybrid Coupled IMUX	Tuning of IMUX can be time consuming and expensive
			Not amenable to change in frequency plan

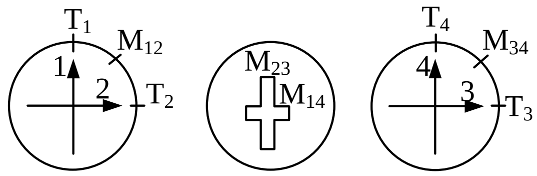


Fig. 5. Representation of mode polarization vectors, tuning screws, coupling screws and coupling irises for dual mode cylindrical waveguide filter. [14]

These dual mode filters are compact in size and light weight, and advanced filtering function realization ability make them an optimum choice for use in communication satellites [15], [17]. Each physical cavity contains two orthogonal TE_{11n} mode resonances generated when a screw at 45 degree perturbs the field, see Fig. 5. These resonance modes exist independently are tuned to their required frequencies by a pair of screws inserted 90 degrees apart at the periphery of the cavity. A screw at 45 degree adjusts the coupling between the resonance modes. The couplings between same polarization modes in

TABLE IV.
Comparison of Various Technologies Available for Channel Filters

Parameter	Coaxial	DR Based	Circular Waveguide	Pre-distorted
Unloaded Q	3000~4000	> 8000	8000~12000	~3000
Size	Small	Small	Large/Medium	Small
Insertion Loss	Low	Low	Low	High
Dual Mode Capability	No	Yes	Yes	No
Spurious Free Window	Large	Small	Medium	Large
Tuning Range	Large	Very Small	Medium	Medium
Realizable Bandwidth	Medium	Small	Medium	Medium
Design Complexity	Medium	High	High	Vey High
Advantages	EM shielding structure	Acceptable temperature stability. Light weight	Negative coupling can be realized in dual mode by changing the position of screw.	Acceptable temperature stability. Light weight
Disadvantages	Very low unloaded Q factor	High cost.	Large in size for low frequencies. Larger size and mass	High Insertion loss and isolator selection is critical.

adjacent cavities are provided by cross-shaped irises placed between the cavities [14], [20].

In case of high frequency selectivity filters, the variations in the group delay are large which causes distortion in data transmission. Therefore, group delay response of the filter should be flattened by employing either external equalizer or self-equalization. The design of the self-equalized filter more difficult as it requires the determination of the group-delay equalization poles than the filter with external equalizer. The mass and volume of self-equalized filter is less than that of filter with external equalizer. It has been shown that the performance of self-equalized 10-4-4 filter (ten pole filter with four real-frequency transmission zeros and four real or complex zeros) is better than 8-4 with an external equalizer [6]−[7].

The channel filters are realized in quasi-Pfitzenmaier topology [11]. The input and output are provided in the adjacent cavities and the coupling-routing diagram is given Fig. 6. The mainline couplings are represented by solid lines the cross-couplings are represented by dotted lines. The dual-mode configuration based on this topology is shown in Fig. 7. This topology can realize up to $N-2$ transmission zeros as folded and Pfitzenmaier topologies do, but with better isolation between input and output. The synthesis of Chebyshev filter functions with transmission zeros in the stopband has been described well in [9]. Similarity transformations [14], [16] have been used to the reconfigure the transversal coupling matrix to the desired

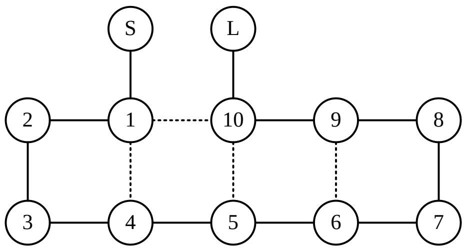


Fig. 6. Quasi-Pfitzenmaier topology for 10th order channel filter (10−4−4); *S* and *L* represents source and load nodes.

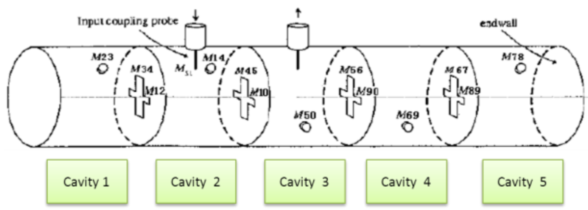
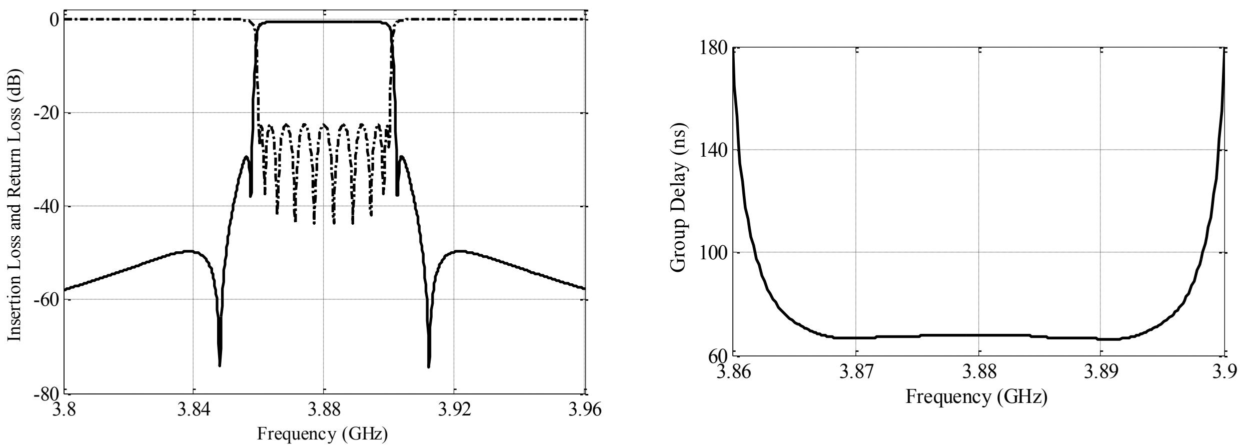


Fig. 7. Dual mode configuration of the 10-4-4 channel filter in quasi-Pfitzenmaier topology.

TABLE V.
COUPLING MATRIX OF IMUX CHANNEL FILERS, R_1=R_N=1.0417

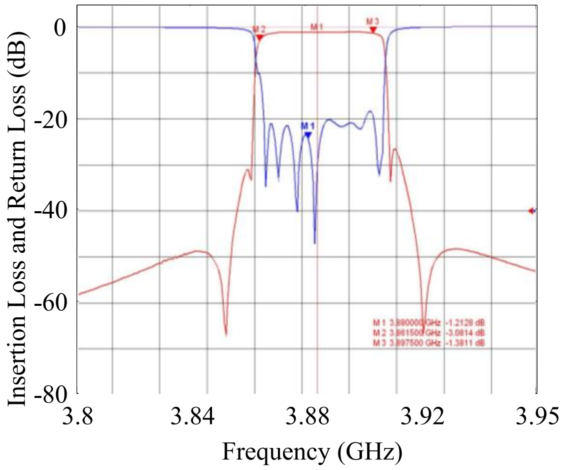
	1	2	3	4	5	6	7	8	9	10
1	0	0.8321	0	0.1136	0	0	0	0	0	0.0102
2	0.8321	0	0.5148	0	0	0	0	0	0	0
3	0	0.5148	0	0.5547	0	0	0	0	0	0
4	0.1136	0	0.5547	0	0.5388	0	0	0	0	0
5	0	0	0	0.5388	0	0.5171	0	0	0	-0.1359
6	0	0	0	0	0.5171	0	0.4602	0	-0.1251	0
7	0	0	0	0	0	0.4602	0	0.7297	0	0
8	0	0	0	0	0	0	0.7297	0	0.5542	0
9	0	0	0	0	0	-0.1251	0	0.5524	0	0.8287
10	0.0102	0	0	0	-0.1359	0	0	0	0.8287	0



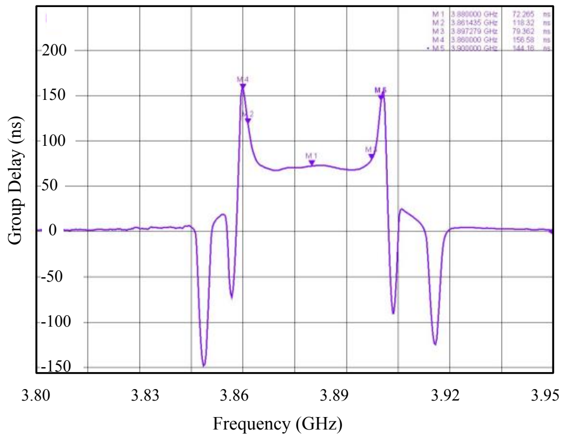
(a) (b)

Fig. 8. Analysis of coupling matrix for 10−4−4 IMUX filter with f_0=3.88 GHz and Qu=10000; (a) Amplitude response; (b) group delay response.

Fig. 9. Developed channel filter for C-band input multiplexer, with center frequency f_0=3.88 GHz.



(a)



(b)

Fig. 10. Measured results of 10th dual mode cylindrical waveguide channel filter, f_0=3.88 GHz; (a) Amplitude response; (b) Group delay response. [24]

coupling matrix. The method described in [25] is used for the reconfiguration of coupling matrix to the desired topology. The coupling matrix is given in Table IV and the amplitude and group delay response of the coupling matrix are given in Fig. 8.

The dimension of the resonant cavities are selected that there is no spurious-mode in the entire frequency range of the multiplexer. The cavities are designed for maximum achievable unloaded *Q* factor to have very small value of insertion loss and sharp rejection response. The diameter *D* and *L* of the cavity are chosen to be 64.80 mm and 54.01 mm respectively. For TE_{111} mode, maximum *Qu* is obtained at *D/L* ratio of 1.20 [20]. All the irises are cross except for M_{45} which is a straight iris as M_{110} coupling is very small. The thickness of each iris is 0.5 mm. The input and output to the filter are provided by the SMA connectors.

Out of five, one channel filters has been developed, and tuned to the desired response. The physical model and measured results of the channel filter are given in Fig. 9 and Fig. 10 respectively. The center frequency, f_0 of the developed channel filter is 3.88 GHz and the design details can be found in [24].

V. System Level Simulation of IMUX

The performance of input multiplexer has been measured after the integration of the channel filters with circulators and isolators according to *channel dropping* configuration. The specifications of circulators and isolators are given in Table VI. In order to incorporate the losses of physical structure, the value of unloaded *Q* has been taken as 10,000 which is quite achievable for dual mode circular waveguide (DMCW) filters at this frequency.

The simulation results are given in Fig. 11. The maximum insertion loss is at center frequency of last channel which is less than 4 dB.

VI. Mechanical Design of IMUX

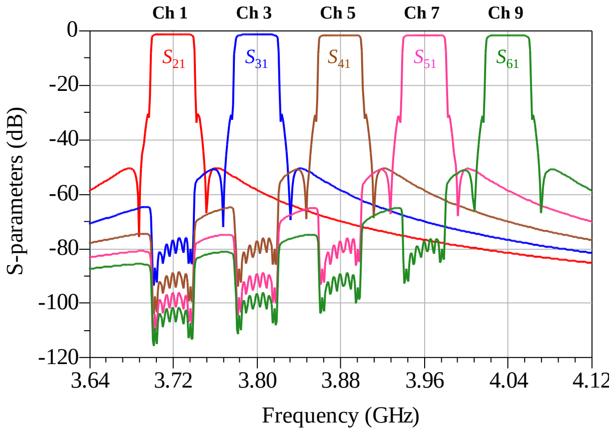
The mechanical model of input multiplexer needs to have an optimal structural design keeping in view the electrical, layout, assembly and EMC aspects as well. The mass of any unit is directly related to the overall cost of the spacecraft. The space-equipment should have lowest possible mass as well as capability of bearing the intense stresses and vibrations during launch. The mechanical model of the input multiplexer is shown in Fig. 12 (a). The total mass of the unit is 5.95 kg and it can be mounted on the satellite panel. The circulators and isolators are fixed with a base which is then mounted on the channel filters. The circulator bracket assembly is shown in Fig. 12 (b). The cavities are joined together by twelve M2.5 screws. The structural analyses have been conducted and the FEM model is shown in Fig. 13. In static structural analysis, the unit is qualified for 12 *g* loading. For dynamic analysis, it is found that no sine-vibration resonance frequency occurs below 100 Hz. The mechanical design ascertains that no resonance amplitude affects the unit and there is sufficient margin of safety.

VII. Conclusion

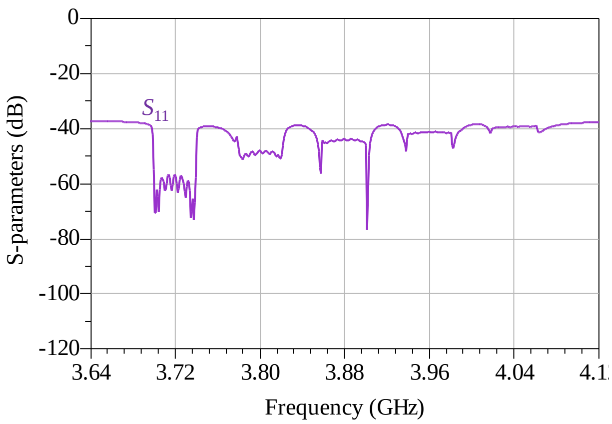
For satellite transponders, the efficient use of available spectrum depends upon channelization of composite signal into various narrowband RF channels with minimum loss of bandwidth and at the same time achieving a certain isolation level among the channels. This paper covers the aspects of input multiplexer design, beginning from the selection of multiplexer configuration and filter technology to the coupling matrix synthesis and

TABLE VI.
SPECIFICATIONS OF CIRCULATORS AND ISOLATORS

Parameter	Specification
Insertion Loss	≤ 0.3 dB
Return Loss	≥ 25 dB
VSWR	≤ 1.20
Isolation	≥ 25~30 dB



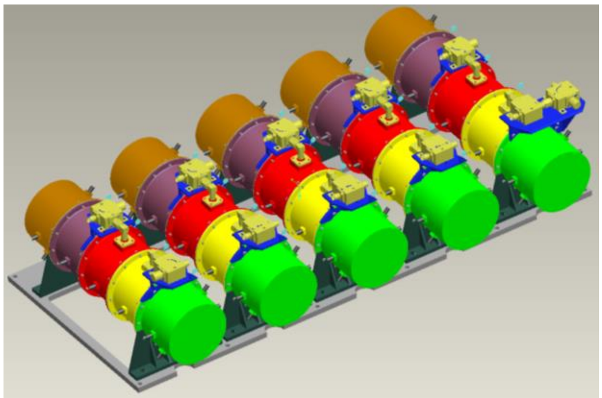
(a)



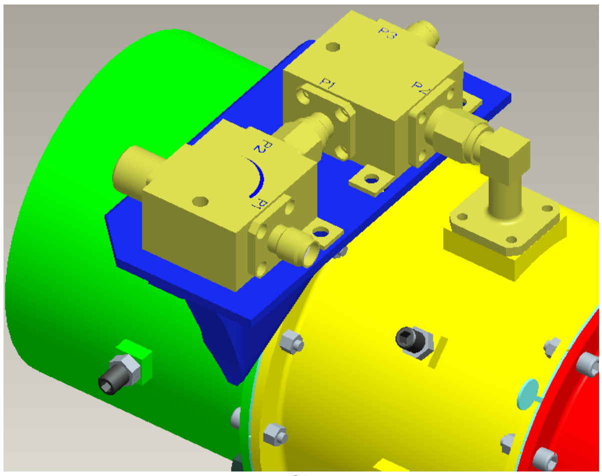
(b)

Fig. 11. Results of system level simulation of 5-channeld C-band input multiplexer, (a) Amplitude response of channel filters (b) Common port return loss.

realization of channel filters. The design of input multiplexer is verified by the performing system simulation of the multiplexer in industry standard circuit simulator. The measured results of channel filter showed a good agreement with simulated results. The mechanical design and analysis ascertain that the multiplexer is capable of withstanding all environmental stress and loads with lowest possible mass.



(a)



(b)

Fig. 12. 3D Mechanical model of 5-channel C-band IMUX; (a) complete unit (b) circulator bracket assembly.

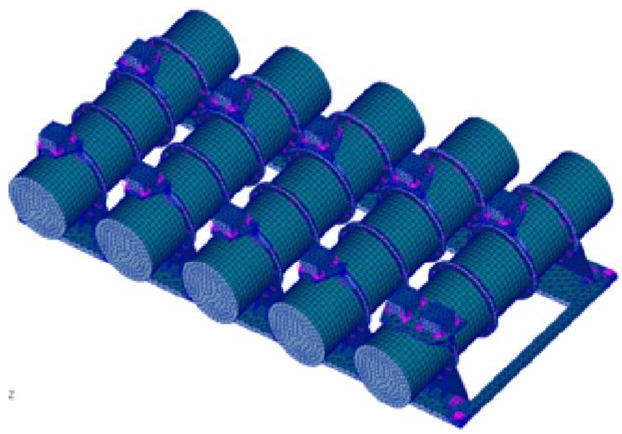


Fig. 13. FEM model for the structural analysis of input multiplexer.

REFERENCES

[1] Richard J. Cameron and Ming Yu, "Design of Manifold-Coupled Multiplexers", *IEEE Microwave Magazine*, Oct. 2007.

[2] Vicente E. Boria and Benito Gimeno, “Waveguide Filter for Satellite”, *IEEE Microwave Magazine*, pp. 60-70, Oct. 2007.

[3] E. G. Cristal and G. L. Matthaei, "Technique for the design of multiplexer having contiguous channels", *IEEE Trans. Microwave Theory Tech.*, pp. 88-93, Jan. 1964.

[4] M. Kunes, "Microwave mu1tiplexers for space applications", *Electronics & Communication Engineering Journal*, Feb, 1998.

[5] C. Kudsia, R. Cameron, andW. Tang, “Innovations in microwave filters and multiplexing networks for communication satellite systems,” *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1133–1149, June 1992.

[6] Ming Yu, Wai-Cheung Tang, Alastair Malarky, Van Dokas, Richard Cameron, and Ying Wang, "Predistortion Technique for Cross-Coupled Filters and Its Application to Satellite Communication Systems", *IEEE Trans. Microwave Theory Tech.*, vol. 51, No. 12 pp. 2205–2215, Dec. 2003.

[7] Ming Yu, David Smith and Mostafa Ismail, "Half-wave Dielectric Rod Resonator Filter", *IEEE MTT-S*, pp. 619-622, 2004.

[8] R. R. Mansour *et al.*, "A 60-Channel Superconductive Input Multiplexer Integrated with Pulse-Tube Cryocoolers", *IEEE Trans. Microwave Theory Tech.*, vol. 48, no. 7, July 2000.

[9] R. J. Cameron, “General prototype network-synthesis methods for microwave filters,” *ESA J.*, vol. 6, pp. 193–206, 1982.

[10] R. R. Mansour *et al*., "Design considerations of superconductive input multiplexer for space applications", *IEEE Trans. Microwave Theory Tech*., MTT-44, July, 1996.

[11] G. Pfitzenmaier, “An exact solution for a six-cavity dual-mode elliptic bandpass filter”, *IEEE MTT-S Int. Microwave Symp Digest.*, pp. 400-403, San Diego, 1977.

[12] F. Arndt, R. Beyer, J.M. Reiter, T. Sieverding, and T. Wolf, “Automated design of waveguide components using hybrid modematchning/numerical EM building-blocks in optimization-oriented CAD frameworks–State-of-the-art and recent advances,” *IEEE Trans. Microwave Theory Tech.*, vol. 45, no. 5, pp. 747–760, May 1997.

[13] Richard J. Cameron, "General Coupling Matrix Synthesis Methods for Chebyshev Filtering Functions", *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 4, Apr. 1999.

[14] R. J. Cameron, C. M. Kudsia, and R. R. Mansour, *Microwave filters for communication systems: fundamentals, design and applications, Wiley*, New York, 2007.

[15] A. E. Atia and A. E. Williams, “New types of bandpass filter for satellite transponders”, *COMSAT Tech.*, pp. 21-43, 1971.

[16] Richard J. Cameron, "Advanced Coupling Matrix Synthesis Techniques for Microwave Filters", *IEEE Trans. Microwave Theory Tech.*, vol. 51, no. 1, Jan 2003.

[17] A. E. Atia and A. E. Williams, “Narrow-bandpass waveguide filters”, *IEEE Trans. Microwave Theory Tech.*,. MTT-20, pp. 258-265, Apr. 1972.

[18] A. E. Atia and A. E. Williams, “Nonminimum-phase optimum-amplitude bandpass waveguide filters”, *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 425-431, Apr. 1974.

[19] A. E. Atia, A. E. Williams, and R. W. Newcomb, “Narrow-band multiple-coupled cavity synthesis,” *IEEE Trans. Circuits Syst.*, vol. CAS-21, pp. 649–655, Sep. 1974.

[20] J. Uher, J. Bornemann, and U. Rosenberg, *Waveguide Components for Antenna Feed Systems: Theory and CAD*. Norwood: Artech House, 1993.

[21] R. E. Collins, *Foundation for microwave Engineering*, McGraw-Hill, New York 1966.

[22] D. Pozar, *Microwave engineering*, 2nd ed. Wiley, New York, 1998.

[23] Ian C. Hunter, Laurent Billonet, Bernard Jarry, and Pierre Guillon, "Microwave Filters—Applications and Technology", *IEEE Trans. Microwave Theory Tech.*, vol. 50, no. 3, Mar. 2002.

[24] Muhammad Latif and Abaid Ullah Salfi, "Design and realization of 10th order (10-4-4) self equalized dual mode waveguide channel filter", *9th IBCAST conf.*, Pakistan, Jan. 2012.

[25] Muhammad Latif and Abaid Ullah Salfi, "General Optimization Algorithm for Reduction of Coupling Matrix of Chebyshev Filtering Functions", *9th IBCAST conf.*, Pakistan, Jan. 2012.