Miniaturized Planar Dual-Band Branch-Line Coupler for Arbitrary Power Division With Four Interior Stubs

V. Vamsi Krishna, B. Gowrish, D. Sivareddy, A.V.G. Subramanyam, V.V. Srinivasan and Y. Mehta
Communication Systems Group, ISRO Satellite Center,
Indian Space Research Organization, Dept. of Space, Govt. of India,
Old Airport Road, Bangalore – 560017, India
vamsikv@isac.gov.in

***Abstract*—This paper presents a design methodology to optimize footprint of miniaturized dual-band branch-line couplers for arbitrary power division, based on pi-shaped shunt open-stub unit. To minimize the physical size of the coupler, the high impedance shunt open-stubs are placed within the interior empty space of the coupler. Design equations are presented explicitly along with graphs. A prototype at L/S-bands is designed and fabricated to validate the approach, which achieves a size reduction by 66% compared with the conventional dual-band branch-line hybrid coupler while providing similar performance and bandwidths.**

***Keywords*—component; formatting; style; styling; insert (*key words*)**

I. INTRODUCTION

Multi-carrier schemes are being incorporated into today's communication standards in the advanced satellite/wireless communication technologies. With the advent of these technologies, compact transceivers operating at multiple separated frequency bands are essential. To accommodate such multiband signal reception and transmission, passive components operating simultaneously at multiple, especially two [1]–[6], frequency bands are attracting wide attention for reducing the size and cost of RF frontend design.

The 90^{o} directional coupler is one of the most fundamental components in microwave circuits among various passive components, which is used extensively in a variety of applications including modulators, mixers, multipliers, power amplifiers, and antenna feed networks [1]. Several approaches have been proposed for design of dual-band couplers [1]–[6] with equal power division and arbitrary power division. Most of the methods use an appropriate dual-band quarter-wavelength impedance transformer to replace the individual branch-lines of the conventional single-band coupler to convert from single- to dual-band operation.

In this paper, a transmission line pi-network topology using two shunt open-stubs, reported in [2], is adopted for dual-band transformation. This topology was presented in [2] for the dual-band coupler design with equal power division. Here, the topology is explored to design a dual-band coupler for arbitrary power division at the two designated bands. Explicit design equations are derived and design graphs are provided. The variation of coupler bandwidths with the arbitrary power division is discussed.

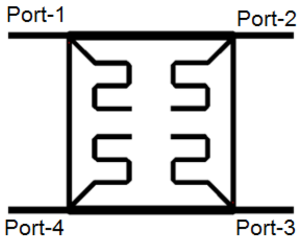


Fig. 1 Present dual-band 90^{0} coupler for arbitrary power division using four interioir open-stubs.

The pi-network topology [2] offers the following advantages over the other topologies: (*i*) all branch lines are only a quarter-wavelength long (compact size), evaluated at the mid-frequency of the two operating bands (*ii*) it provides a much wider operating (*iii*) design include only three circuit parameters (impedances) and (*iv*) geometry is amenable for convenient meandering of lines.

Further, to minimize the physical size of the coupler, the high impedance shunt open-stubs are placed within the interior empty space of the coupler, as shown in Fig. 1. This achieves a size reduction by 66% compared with the conventional design [2]. It has been shown that couplers may have arbitrary output power division by controlling the characteristic impedances of the sections. The purpose of this paper is to extend their formulations to develop dual-band branch-line and rat-race couplers with arbitrary power divisions at the two designated bands. These couplers will be useful for dual-band mixers and antenna arrays.

II. ANALYSIS AND DESIGN

A. Conventional Coupler for Arbitrary Power Division

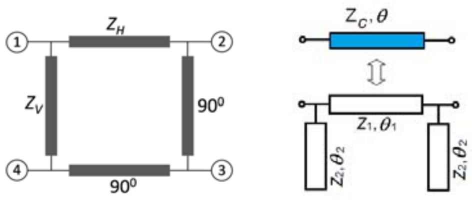
The conventional single-band branch-line coupler is shown in Fig. 2(a). For arbitrary power division, let the difference in magnitudes at the through and coupled ports is *P*, defined as

$$\left|S_{21}\right| - \left|S_{31}\right| = P \quad (dB) \text{ and } \beta = 10^{(P/20)} \tag{1}$$

The generalized characteristic impedances Z_H and Z_V, for a system reference impedance of Z_0, are given as [7] – [9]

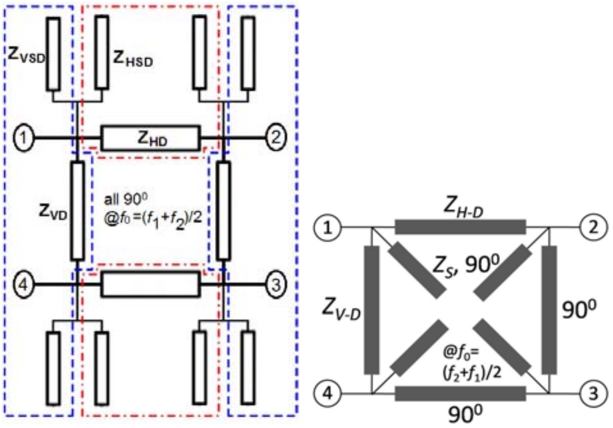
$$Z_H = Z_0\left[\beta\Big/\sqrt{1+\beta^2}\right] \tag{2a}$$

$$Z_V = Z_0\beta \tag{2b}$$



(a) (b)

Fig. 2 Topology of (a) Convnetional single-band branch-line coupler for arbitrary powwer division (b) Pi-type dual-band transmformer equivelent to a transmission line [2].



(a) (b)

Fig. 3 Topology of (a) dual-band branch-line coupler for arbitrary powwer division using transmission line equivelent Pi-type dual-band transmformers (b) Final dual-band branch-line couple with four stubs, $Z_S=(Z_{HSD}//Z_{VSD})$

B. Dual-band Transformer Using Π-shaped Open-Stub Unit

Fig. 2(b) shows the double-stub unit equivalent to conventional transmission line [2], which is used to replicate the sections of the conventional coupler. It is composed of a transmission line section (Z_1, θ_1) with two shunt stubs (Z_2, θ_2) attached at the ends [10]. Equivalence between this unit and the original $\lambda_g/4$ transmission line section (Z_c, θ) is now obtained using *ABCD* matrices [10] as

$$Z_1 = Z_c \csc\theta_1 \tag{3a}$$

$$Z_2 = Z_1 \tan\theta_1 \tan\theta_2 \tag{3b}$$

C. Dual-band Coupler for Arbitrary Power Division

Assume $\theta_1=\theta_2$. For dual-band operation, the basic stub-loaded unit has to imitate an electric length of 90° and different equivalent characteristic impedances at the two designated frequencies, denoted as f_1, f_2 (let the midband frequency is $f_0 = (f_1 + f_2)/2$) to perform the dual-band operation. If $\theta_{f1}$and θ_{f2} are the electrical lengths at the two frequencies f_1 and f_2, respectively, then using (3), the impedance relations for dual-band operation are

$$Z_1 = \pm Z_c \csc\theta_{f1} \text{ and } Z_1 = \pm Z_c \csc\theta_{f2} \tag{4a}$$

$$Z_2 = \pm Z_1 \tan^2\theta_{f1} \text{ and } Z_2 = \pm Z_1 \tan^2\theta_{f2} \tag{4b}$$

The general solution for (4) is

$$\theta_{f_2} = n\pi - \theta_{f_1} \tag{5}$$

TABLE I. Generalized Expressions for Circuit Parameters of Arbitrary Power Division Dualband Coupler

Imp.	Dual-band [2] for Equal Power Division	Dual-band for Arbitrary Power Division
$Z_{H\text{-}D}$	$\frac{Z_0}{\sqrt{2}}\csc\left(\frac{\pi}{1+n}\right)$	$Z_0\frac{\beta}{\sqrt{1+\beta^2}}\csc\left(\frac{\pi}{1+n}\right)$
$Z_{V\text{-}D}$	$Z_0\csc\left(\frac{\pi}{1+n}\right)$	$Z_0\beta\csc\left(\frac{\pi}{1+n}\right)$
Z_S	$\frac{Z_0}{1+\sqrt{2}}\sec\left(\frac{\pi}{1+n}\right)\tan\left(\frac{\pi}{1+n}\right)$	$\frac{Z_0\beta}{1+\sqrt{1+\beta^2}}\sec\left(\frac{\pi}{1+n}\right)\tan\left(\frac{\pi}{1+n}\right)$

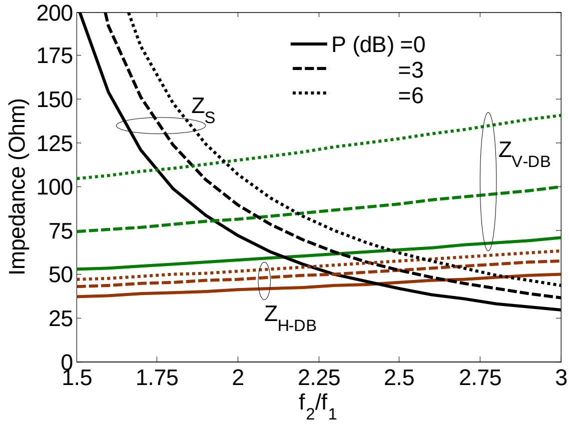


Fig. 4 Impedance solitions for differrent frequency ratios for the dual-band arbitrary power division hybrid.

The electrical length θ_0 at f_0 is given by

$$\theta_0 = \left(\theta_{f1}+\theta_{f2}\right)/2 = n\pi/2 \text{ where } f_1/f_2 = \theta_{f1}/\theta_{f2} \tag{6}$$

Then the electrical lengths at the dual-band frequencies, in terms of frequency ratio, f_2/f_1, using (5) and (6) are derived as

$$\theta_{f_1} = n\pi/\left[1+(f2/f1)\right] \text{ and } \theta_{f_2} = n\pi(f2/f1)/\left[1+(f2/f1)\right] \tag{7}$$

Substituting (7) in (4) for the dual-band element at f_1 yields

$$Z_{1D} = Z_c \csc\left(\frac{n\pi}{1+(f2/f1)}\right) \text{ and}$$

$$Z_{2D} = Z_{1D}\tan^2\left(\frac{n\pi}{1+(f2/f1)}\right) \tag{8}$$

The suffix '*D*' denotes dual-band in (8). Now the conventional single-band coupler for arbitrary power division is transformed to a dual-band coupler by replacing Z_c in (8) by the impedances Z_H and Z_V in (1) for the corresponding horizontal and vertical lines, respectively. These are denoted by Z_{HD} and Z_{VD}, while the corresponding stub impedances are Z_{HSD} and Z_{VSD}, respectively. Let $K=f_2/f_1$ and for n=1, these are

$$Z_{HD} = Z_0\left(\beta/\sqrt{1+\beta^2}\right)\csc\left(\pi/(1+K)\right) \text{ and}$$

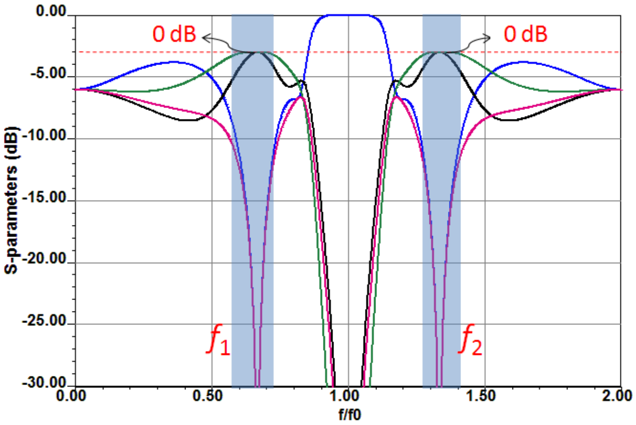
$$Z_{HSD} = Z_{H-D}\tan^2\left(\pi/(1+K)\right) \tag{9}$$

$$Z_{VD} = Z_0\beta\csc\left(\pi/(1+K)\right) \text{ and}$$

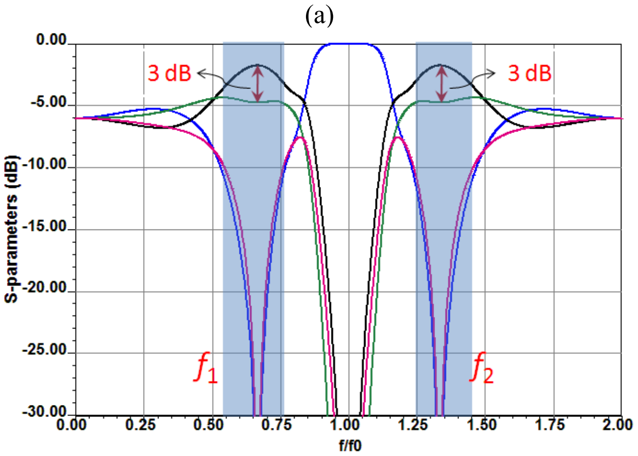
$$Z_{VSD} = Z_{VD}\tan^2\left(\pi/(1+K)\right) \tag{10}$$

TABLE II. IMPEDANCES FOR DUALBAND COUPLER FOR K=2

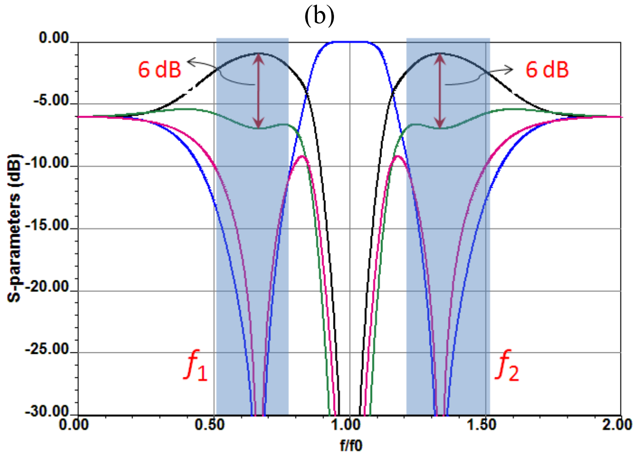
Power Division parameter, P (dB)	Z_{HD} (Ω)	Z_{VD} (Ω)	Z_S (Ω)
0 (equal split)	40.83	57.73	71.74
3	47.12	81.55	89.59
6	51.61	115.2	106.93
10	55.05	182.57	126.89



(a)



(b)

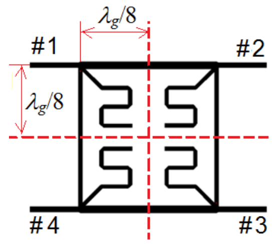


(c)

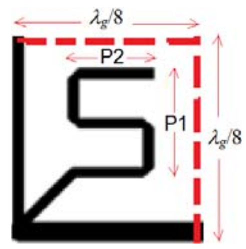
Fig. 5 Circuit computed responses of the dual-band arbitrary power division hybrid coupler with f_2/f_1=2 for (a) P=0, (b) P=3 and (c) P= 6 [Notation: S_{11}- Blue; S_{41}- Red; S_{21}- Black; S_{31}- Green]

The overall stub impedance in Fig. 3(b) is

$$Z_S = (Z_{HSD} // Z_{VSD}) = \frac{Z_0\beta}{1+\sqrt{1+\beta^2}}\sec\left(\frac{\pi}{1+K}\right)\tan\left(\frac{\pi}{1+K}\right) \quad (11)$$



(a)



(b)

Fig. 6 Layout of the (a) proposed dual-band arbitrary power divison coupler using interior stubs (b) S-shaped meadered stub.

The generalized circuit parameters for the dual-band coupler with arbitrary power division are given in Table I, where the expressions for dual-band coupler [2] for equal power division are compared. Figure 4 plots the impedances solutions for the present dual-band hybrid coupler for frequency ratio varying from 1.5 to 3.0 for arbitrary power divisions of P = 0, 3 and 6 dB. The frequency ratio range is based on the highest realizable impedance which is considered here is up to 200Ω. It is observed that the horizontal and vertical line impedances increase, while the stub impedance decreases with f_2/f_1, In contrast, for any fixed f_2/f_1, all impedances increase with unequal-power division factor P.

As an example, Table II gives the impedances of the dual-band coupler with f_2/f_1 = 2 for arbitrary power divisions, P = 0 (equal split), 3, 6 and 10 dB. It is observed that the vertical line impedance is so high for the coupler with P = 10. Next, to illustrate the dual-band hybrid performances, Fig. 5 shows the normalized frequency responses (with respect to the mid frequency, f_0) of the dual-band coupler with f_2/f_1 = 2 for power division of P = 0, 3 and 6 dB. An important observation in terms of the coupler bandwidths (10 dB return loss level being the reference) is that the operating bandwidth at f_1 and f_2 increases with P.

III. IMPLEMENTATION AND MEASURED RESULTS

For validation purposes, a microstrip prototype dual-band coupler operating at L/S bands of IRNSS satellite applications: f_1=1.2 GHz and f_2=2.5 GHz (f_2/f_1=2.08) with equal power division at the two bands (P=0) is fabricated on a 15 mil thick RT/Duroid 5870 substrate (ε_r=2.33, tanδ=0.0009).

A. *Miniaturization Using Interior Stubs*

The coupler occupies a very large circuit size when implemented using the layout in [2]. From the above analysis and from Fig. 4, it is observed that the required open-stub impedance is high (> 50Ω) for f_2/f_1 up to 2.25, which occupies a narrow line width and hence facilitates meandering. Here, the interior free space in utilized optimally to incorporate all the open-stubs by suitable meandering into S-shape as shown in Fig. 6(a). As shown in Fig. 6(b), the maximum area available for each stub is only $\lambda_g/8\times\lambda_g/8$. Here, the stub is meandered into S-shape within the size and also sufficient gap is provided to avoid the unwanted inter stub coupling. This enables significant size reduction, about one-third, for the dual-band coupler of when compared to the conventional deign [2].

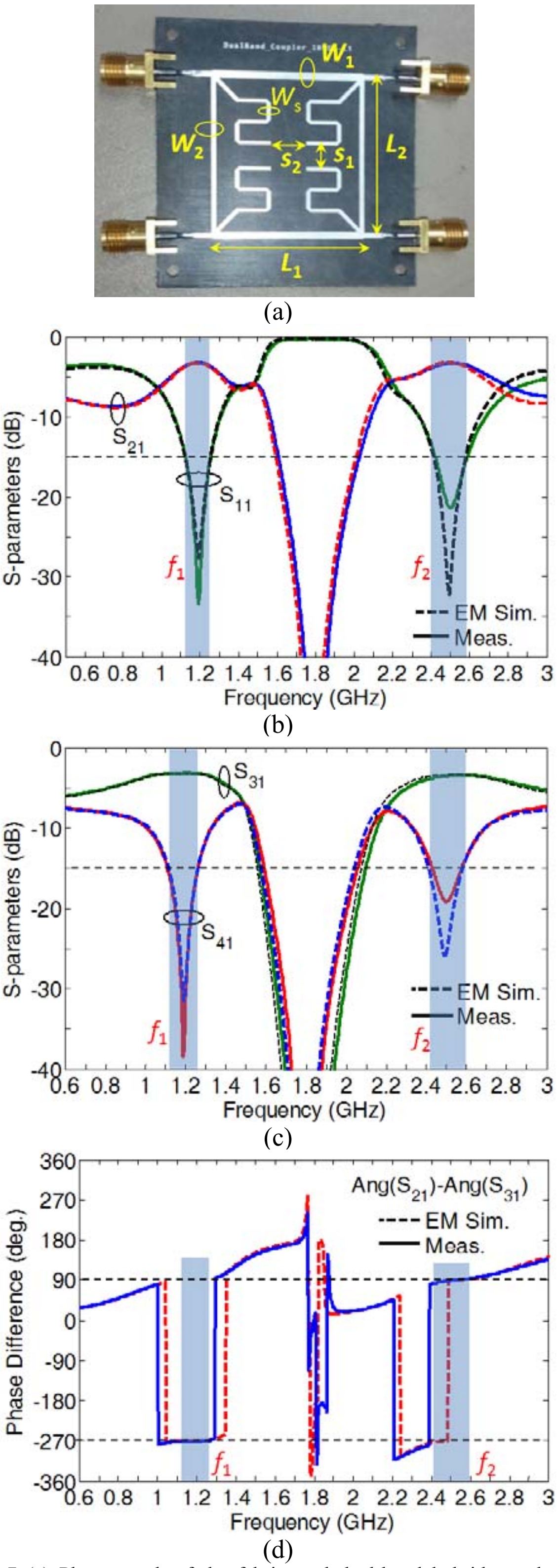


Fig. 7 (a) Photograpgh of the fabriccated dual-band hybrid coupler for equal power division, P=0 (W_1= 1.3 mm, L_1= 28.7 mm, W_2= 0.8 mm, L_2 = 29.1 mm, W_s= 0.6 mm, s_1= 5.1mm, s_2 = 4.2 mm.). Simulated and measured responses (b) S_{11}, S_{21} (c) S_{31}, S_{41} and (d) Phase differenc.

B. Fabrication and Measurements

The fabricated photograph is shown in Fig. 7(a). The simulated and measured magnitude responses of the present coupler are shown in Fig. 7(b) and (c), while Fig. 7(d) shows the measured phase difference responses. Excellent agreement is observed between the simulated and measured ones.

The measured return loss is better than 30 (20) dB at f_1 (f_2). The measured insertion loss and coupling loss are better than 3.2 dB, 3.1 dB (3.2 dB, 3.3 dB) dB at f_1 (f_2), while the measured isolation is better than 30 (19) dB at f_1 (f_2). Further, the final coupler and exhibits good phase response and bandwidths at the two frequencies.

IV. Conclusion

A miniaturized dual-band 90° hybrid coupler for arbitrary power division in the two bands is presented. The present approach is based on two shunt open-stub unit, where the stubs are meandered in S-shape and placed in the inner area of the coupler to achieve miniaturization of about 66%. Design equations and graphs are provided. A prototype operating at 1.2/2.5 GHz frequencies with equal power division was fabricated. Compared to other techniques, the present method exhibits good bandwidths at two frequencies along with high rejection between the bands.

References

[1] C. Collado, A. Grau, and F. D. Flaviis, "Dual-band planar Quadrature hybrid with enhanced bandwidth response," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 1, pp. 180–188, Jan. 2006.

[2] K.-K. M. Cheng and F.-L.Wong, "A novel approach to the design and implementation of dual-band compact planar 90^0 branch line coupler," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 11, pp. 2458–2463, Nov. 2004.

[3] H. Zhang and K. J. Chen, "A stub tapped branch line coupler for dualband operations," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 2, pp. 106–108, Feb. 2007.

[4] M-J. Park, "Dual-band, unequal length branh-line couplr with centre-tapped stubs," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 10, pp. 617–619, Oct. 2009.

[5] C.-L. Hsu, J.-T. Kuo, and C.-W. Chang, "Miniaturized dual-band hybrid couplers with arbitrary power division ratios," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 1, pp. 149–156, Jan. 2009.

[6] K-S. Chin, K-M. Lin, Y-H. Wei, T-H. Tseng, and Y-J. Yang, "Compact dual-band branch-line and rat-race couplers with stepped impedance stub lines," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 5, pp. 1213–1221, May. 2010.

[7] C. Y. Pon, "Hybrid-ring directional coupler for arbitrary power division," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-19, no. 11, pp. 529–535, Nov. 1961.

[8] R. Levy and L. J. Lind, "Synthesis of symmetric branch line guide directional couplers," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-16, no. 12, pp. 80–89, Dec. 1968.

[9] G. L. Matthaei, L. Young, and E. M. T. Jones*, Microwave Filters, Impedance-Matching Network, and Coupling Structures*. Norwood, MA: Artech House, 1980, ch. 13.

[10] V. K. Velidi, A. Bhattacharya, "Miniaturized planar 90^0 hybrid coupler with unchanged bandwidth using single characteristic impedance line," *Microwave Conf. China-Japan joint,* pp.396-399, 10-12 Sept. 2008.

Vamsk K. Velidi received the M. Tech and Ph. D degrees in RF & Microwave Engineering from the IIT-Kharagpur, India in 2008 and 2012, respectively. In 2011, he joined the ISRO Satellite Centre, Bangalore, as an Engineer in the Communication Systems Group, where he is working on the design and development of high performance passive components for various Spacecraft and ground applications. He has authored/co-authored around 42 papers in journals and conferences. His current research interests include CAD/experimental characterization of passive microwave circuits using planar/waveguide/substrate-integrated-waveguide and semiconductor technologies. He received the '*IEEE Publication/Patent Award-2014*' in Journal Category from IEEE Bangalore Section. He is nominated and shortlisted for the '*Innovative Student Project Awards-2013*' at the Ph.D level by Indian National Academy of Engineering (INAE), New Delhi, India. He is serving in the review board of international journals IEEE TMTT & MWCL, IET-MAP, ETRI, and Elsevier-AEUE. Since 2015, he serves as the Editor Board Member for *Int. Jour. of RF and Microwave Computer-Aided Engineering*.

Gowrish B received the M.Tech degree in RF design and technology (RFDT) in CARE, IIT Delhi, in 2013. He has worked on NRD Guide at 60 GHz, power combiners for Doherty power amplifiers, PCB antennas at 2.4 GHz. Since 2014 he is working as an engineer in Communication Systems Group in ISRO Satellite Centre, Bangalore. His current areas of research are design of dielectric resonator based filters, co-axial cavity-based filters for satellite application, passive system design using waveguide and microstrip technology. He has eight publications till date including seven conferences and one journal, and has authored product application notes on antenna design for wireless consumer products.

Sivareddy D received the B.E degree in Electronics & Communication Engr. from Andhra University in 2002 and the M. Tech degree in Microwave Engineering from IT-BHU in 2004. He joined Communications Systems Group of ISRO Satellite Centre, Bangalore, as a Scientist in 2004. His research interests are in the area of waveguide and microstrip passive components, antennas and RF MEMS. He is the recipient of ISRO's Young Scientist Merit Award-2011 and as a team member received 'Team Excellence Award-2013' of ISRO for his contribution in the communication systems design of Mars Orbiter Mission.

A. V. G. Subramanyam, obtained his B.Tech (ECE) in 1994 from JNT University, M.Tech (Microwave Electronics) in 1996 from Delhi University, and Ph. D degree in 2015 from IIT Kharagpur. From 1997-199, he worked as Scientist in Department of Electronics (present DIT), Directorate of Standardization Testing and Quality Certification. Since 1999, he is with Communication Systems Group of ISRO Satellite Centre, Bangalore. He was Deputy Project director for GSAT-16 project and Project Manager for Meghatropiques, GSAT-2&3 projects. Currently he is heading Passive Systems Section and involved in design and development of high performance passive devices for various spacecraft and ground applications. He is a member of the team that received 'Team Excellence Award-2013' of ISRO for his contribution in the communication systems design of Mars Orbiter Mission. His interests include high power waveguide components and microwave miniature components using Waveguide, PCB and MEMS technologies. He has published 28 technical papers in various conferences and journals.

V. V. Srinivasan obtained his M.Tech degree in Microwave Electronics from Delhi University, India, in 1986. He joined the Communication Systems Group of ISRO Satellite Centre, Bangalore in 1986 and currently heading the Antenna & Passive Systems Division. His area of work is in phased array antennas, microstrip antenna arrays, large ground station reflector antennas, feeds for ground systems etc. He has published more than 70 technical papers in various conferences and journals. He served the IEEE Bangalore section in various capacities and Chaired the section in 2010 and 2011. He is a recipient of National Research Development Corporation (NRDC), India award in 1998 for a novel antenna feed development and IETE's Prof. S. N. Mitra Memorial Award in 2002. He is a member of the team that received 'Team Excellence Award-2007' of ISRO for his contribution in the design of IDSN-32 & Phased Array Antenna and also 'Team Excellence Award-2013' of ISRO for his contribution in the communication systems design of Mars Orbiter Mission.

Y. Mehta obtained his B.E (Electronics) from Shri GS Institute of Technology and Science, Indore, Devi Ahilya Vishwavidyalaya, Indore in 1977. He joined Communication Section of ISRO Satellite Centre, Bangalore in January 1979. He has designed and developed S-band TT&C Transponder for IRS series of satellites and C-band Telemetry transmitter for various GEO Missions. Presently he is heading the Communication Systems Group as Group Director. He is the recipent of Astronautical Society of India (ASI) Award-2011 for his contribution in Spacecraft and related technologies. He is the team leader of the team that received 'Team Excellence Award-2013' of ISRO for his contribution in the communication systems of Mars Orbiter Mission.