All-Planar Dual-Mode Asymmetric Filters at Ka-Band

Ho-Chung Chen and Ching-Kuang C. Tzuang, *Fellow, IEEE*

***Abstract*—All-planar dual-mode inductive asymmetric filters utilizing new planar microstrip to dielectric-loaded rectangular waveguide transitions at Ka-band were presented and built in this letter. The conventional, three-dimensional metallic rectangular waveguide dual-mode filters can be implemented into mature PCB technology with a much easier and lower-cost fabrication process on the basis of the all-planar feature of the transition. This work demonstrates two Ka-band filter examples with center frequency at 31 GHz and bandwidth at 1 GHz and 2 GHz. The measured minimum insertion loss of each case was, respectively, 2.68 and 1.12 dB, with greater than 10 dB return loss in the passband. Moreover, the measured side-band attenuation (near passband) is larger than 30 dB due to the transmission zeros at each side of the passband.**

***Index Terms*—Dual-mode, filter, Ka-band, planar transition.**

I. Introduction

FILTERS play critical roles in many RF/microwave applications. Dual-mode filters, with optimum frequency selectivity, smaller size, and high stopband attenuation, have been used for mobile and satellite communications systems. Many researchers have presented numerous dual-mode filters utilizing metallic circular waveguides [1], metallic rectangular waveguides [2], [3], and microstrip [4], [5]. Based on the metallic waveguides, the dual-mode filters have excellent low insertion losses. However, these metallic structures desire another transitions to connect planar circuits with metallic filters and the original three-dimensional (3-D) structures become more complex and bulky. Since printed circuit board (PCB) fabrication produces compact filter structures, the microstrip dual-mode filter appears to be one of the appropriate choices for integrating all the RF front-end components into one module. However, the critical radiation loss at millimeter-wave frequencies negatively impacts the planar microstrip filters. The quality factor of the microstrip ($\varepsilon_r = 3.02$) is about 10, which can not match the quality factor of the metallic rectangular waveguide near 310 using the same structure height (0.5 mm) at Ka-Band [6].

In this letter, all-planar dual-mode filters at Ka-band utilizing new planar microstrips to dielectric-loaded waveguide transitions [7] are reported (Fig. 1). The planar transition can successfully transform microstrip modal energy to the dielectric-loaded rectangular waveguide using the same substrate coated with metallic plates and sidewalls. On the other hand, this structure can circumvent the critical radiation loss at millimeter-wave frequencies. Relying on the simple structures of the asymmetric inductive discontinuities between rectangular waveguides [3], the presented dual-mode filters can be analyzed and optimized by mature commercial finite-element simulators such as Ansoft HFSS™. As anticipated, the planar transition features all-planar PCB integration of dual-mode filter and low-loss merit of the rectangular waveguide. Meanwhile, the overall performance of the all-planar, dual-mode filter including both planar transitions and rectangular waveguide dual-mode filters, will be presented.

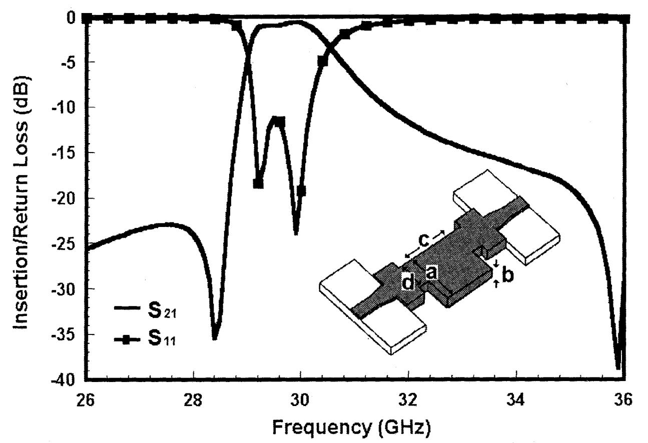

Fig. 1. Single-cavity dual-mode filter and its theoretical frequency responses. Each dual-mode cavity produces two transmission poles and one transmission zero. The parameters: $a = 6.26$ mm, $b = 0.508$ mm, $c = 5.44$ mm, $d = 2.5$ mm, and $\varepsilon_r = 3.38$.

II. Design of Planar, Dual-Mode Filter

Fig. 1 depicts the structure of the single cavity dual-mode filter and its frequency responses. The dual-mode cavity shown in Fig. 1 contains two orthogonal modes and produces two transmission poles and one transmission zero [3]. Since the opposite directions of the magnitude between the two orthogonal modes in the cavity vanish the transmission path and create the transmission zero, the transmission zero can be located on the right side or left side of the passband by modifying the dimensions of the cavity to control the quantity of the negative coupling between the two modes. The closer the transmission zeros to the cutoff frequency, the sharper the filter skirt and the higher the selectivity. Accordingly, the design flow of the dual-mode filter is composed of the following steps. First, we determine the center

Manuscript received May 28, 2002; revised August 29, 2002. This work was supported by the Ministry of Education (MOE) program for Promoting Academic Excellent of Universities under Grant 89-E-FA06-2-4. The review of this letter was arranged by Associate Editor Dr. Rüdiger Vahldieck.

The authors are with the Institute of Electrical Communication Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: cktzuang@cc.nctu.edu.tw).

Digital Object Identifier 10.1109/LMWC.2003.810119

1531-1309/03$17.00 © 2003 IEEE

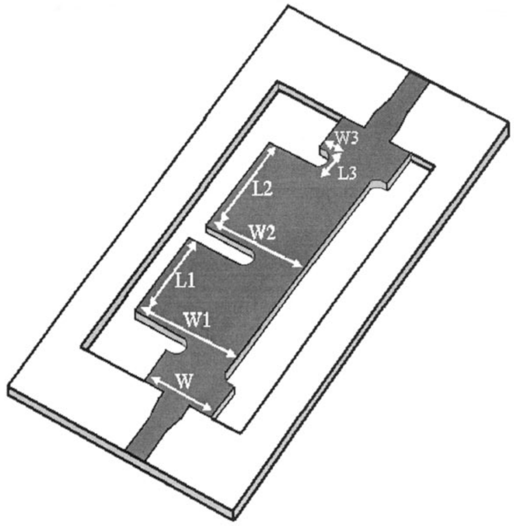

Fig. 2. Dual-mode filter with two planar microstrip to dielectric-loaded waveguide transitions and two coupling resonators.

frequency of the filter. After choosing TE_{mnl} and TE_{pqr} two orthogonal modes, the resonant frequency f_0 can be estimated by

$$f_0 = \frac{u_p}{2\times\pi}\times\sqrt{\left(\frac{m\pi}{a}\right)^2+\left(\frac{n\pi}{b}\right)^2+\left(\frac{l\pi}{c}\right)^2}$$
$$= \frac{u_p}{2\times\pi}\times\sqrt{\left(\frac{p\pi}{a}\right)^2+\left(\frac{q\pi}{b}\right)^2+\left(\frac{r\pi}{c}\right)^2} \quad (1)$$

where u_p is $c_0/\sqrt{u_r\times\varepsilon_r}$ and c_0 is the velocity of electromagnetic wave in free space. u_r and ε_r are relative permeability and permittivity of the substrate, respectively. The parameters a, b and c are respectively the width, height and length of the cavity defined in Fig. 1. The parameters n and q are chosen to be zero since a and c are much larger than b, the parameters m, n, l and p, q, r are all positive integers. The initial waveguide dimension ratio (a/c) can then be acquired by

$$\frac{a}{c}=\sqrt{\frac{m^2-p^2}{r^2-l^2}}. \quad (2)$$

If TE_{102} and TE_{201} modes are chosen, the ratio of parameter a over c will equal to one. Second, The parameter d, the width of coupling iris, controls the filter bandwidth, the wider the parameter d, the larger the filter bandwidth. Next, we determine the position of the transmission zero. Adjusting parameter a, one may freely position the transmission zero at either high side or low side of the passband skirts. When doing so, one should change parameter c so that f_0 is maintained nearly the same according to (1). Finally, the peripheries of the all-planar filter are made by routing the PCB during fabrication, resulting in rounded corners at the waveguide discontinuities, which affect the filter characteristics and can be compensated by tuning parameters a and c utilizing HFSS™. As seen in Fig. 1, two transmission poles and one transmission zero at the lower skirt of the passband are obtained for the dual-mode filter centered at 29.5 GHz with 1 GHz bandwidth following the design procedure mentioned above.

In the following examples, this letter presents measured results for two all-planar, dual-mode dual-cavity bandpass filters with transmission zeros at both high- and low-side skirts of the filter passband. Fig. 2 shows the schematic of such filters. Microstrip modes are launched at two far ends with ground plane underneath the substrate. The tapered microstrip facilitates the planar transition, converting microstrip mode into TE_{10} mode of the rectangular waveguide of width W and height 0.508 mm. Through the irises of width $(W-2\times W3)$, the TE_{10} mode is sequentially coupled to the two, dual-mode cavities, which support TE_{102} and TE_{201} resonant modes, and finally reaches the output port. Table I lists the values of the structural parameters of the Ka-band filters with a 1 and 2-GHz bandwidth centered at 31 GHz. Varying the structure dimensions of Table I by ± 0.1 mm, we obtain the simulated sensitivity analyzes showing that the parameters $W1$ and $W2$ are the most sensitive parameters to manufacturing tolerances. The transmission zero related to $W1(W2)$ will be shifted ∓ 0.6 GHz under the varied ± 0.1 mm of $W1(W2)$. When making the filter, care should be exercised with the sensitive parameters.

TABLE I
DIMENSIONS OF THE DUAL-MODE FILTERS

Bandwidth	1 GHz	2 GHz
W (mm)	4.1	4.1
W1 (mm)	5.53	5.55
W2 (mm)	6.14	6.5
W3 (mm)	0.8	0.65
L1 (mm)	5.9	5.4
L2 (mm)	4.3	4.5
L3 (mm)	1	1

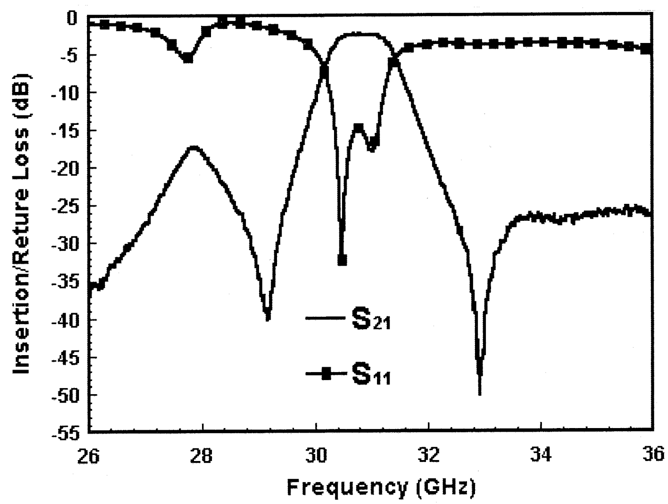

Fig. 3. Measured responses of Ka-band dual-mode filter with 1-GHz bandwidth.

III. FABRICATION AND MEASUREMENT RESULTS

The Ka-band dual-mode filters are implemented on the RO4003™ substrate of thickness 0.508 mm, relative dielectric constant 3.38, metal thickness 17 μm, and loss tangent 0.002. After chemical etching, the pattern of the transitions, and the filter on the top plate, the side walls of the PCB are processed first by routing the peripheries and followed by copper-plating to connect the top and bottom metal surfaces to

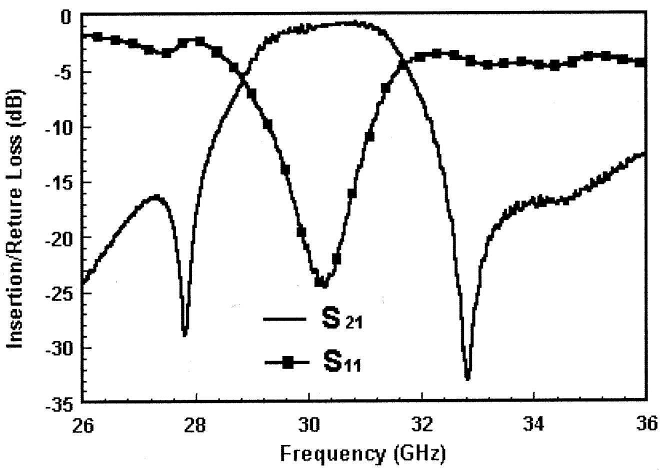

Fig. 4. Measured responses of Ka-band dual-mode filter with 2-GHz bandwidth.

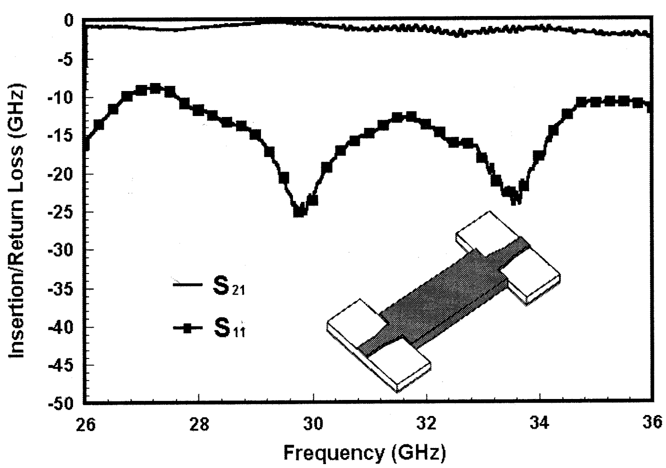

Fig. 5. Measured performance of the all-planar Ka-band transition.

realize the dielectric-loaded waveguides and junctions. Thus, the microstrip ground plane is dc-connected to the filter, which is truly commensurate with planar PCB technology. Fig. 3 plots the measured frequency responses of the dual-mode filter with 1-GHz bandwidth. The measured minimum insertion loss is approximately 2.68 dB and the minimum return loss is larger than 15 dB in the passband. Two transmission zeros are observed at 29.2 and 33 GHz, providing more than 35 dB of stop band rejection. Fig. 4 displays the measured frequency responses of the dual-mode filter with 2-GHz bandwidth and two transmission zeros are located at 27.6 and 32.8 GHz with over 30 dB of stopband rejection. The measured minimum insertion loss is around 1.12 dB at 31 GHz. Fig. 5 displays the back-to-back connected planar transitions and the measured frequency responses. The total length of the structure in Fig. 5 is the same as that of the dual-mode filters just reported and the insertion loss is nearly 1 dB at 31 GHz. Therefore, compared with Figs. 3 and 4, we can extract the minimum insertion losses of the coupling irises are respectively 1.68 dB and 0.12 dB for various bandwidths. Based on the measured data, we observe that filter with wider bandwidth is less sensitive to manufacturing tolerances and lower insertion losses. The attractive performance reveals that the Ka-band dual-mode filters are viable alternatives for integrating millimeter-wave transceiver modules.

IV. Conclusion

In this letter, Ka-band all-planar inductive dual-mode filters utilizing tapered microstrip to dielectric-loaded waveguide transitions were presented and investigated theoretically and experimentally. Compared with conventional three-dimensional metallic structures, the presented all-planar inductive dual-mode filters are relatively small and light weight. They can be realized by mature PCB technology for mass production and cost reduction. The passband losses of the all-planar dual-mode filters are primarily limited by the quality factors of the dielectric-loaded rectangular waveguide resonator. Both theoretical and measured data show that the proposed dual-mode filters utilizing PCB realization have great potential for millimeter-wave integrated transceiver design.

References

[1] A. E. Williams, "A four-cavity elliptic waveguide filter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 1104–1109, Dec. 1970.

[2] J. F. Liang, X. P. Liang, K. A. Zaki, and A. E. Atia, "Dual-mode dielectric or air-filled rectangular waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1330–1336, July 1994.

[3] M. Guglielmi, O. Roquebrun, P. Jarry, E. Kerherve, M. Capurso, and M. Piloni, "Low-cost dual-mode asymmetric filters in rectangular waveguide," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 3, 2001, pp. 1787–1790.

[4] M. G. Banciu and R. Ramer, "Design of microstrip dual-mode filters using finite-difference time-domain method," in *Proc. Asia-Pacific Microwave Conf.*, Dec. 2000, pp. 975–978.

[5] L. Zhu, P. M. Wecowski, and K. Wu, "New planar dual-mode filter using cross-slotted patch resonator for simultaneous size and loss reduction," *IEEE Trans. Microwave Theory Tech.*, vol. 47, pp. 650–654, May 1999.

[6] K. C. Gupta, *Microstrip Lines and Slotlines*, 2nd ed. Boston, MA: Artech House, Mar. 1996.

[7] C. K. Tzuang, K. C. Chen, C. J. Lee, C. C. Ho, and H. S. Wu, "H-plane mode conversion and application in printed microwave integrated circuit," in *Proc. Eur. Microwave Conf.* , vol. 2, Oct. 2000, pp. 37–40.