SYNTHESIS OF DIRECT-COUPLED WAVEGUIDE FILTERS FOR INTEGRATED FRONT-END APPLICATIONS

Jens Bornemann*, Jaroslaw Uher+

* Laboratory for Lightwave Electronics, Microwaves and Communications (LLiMiC), Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada V8W 3P6

\+ Satellite and Communication System Division, Spar Aerospace Ltd., Ste-Anne-de-Bellevue, PQ, Canada H9X 3R2

Abstract - A field-theory-based synthesis technique for the design of direct-coupled waveguide bandpass filters for integrated front-end applications is introduced. A nonsymmetric inverter circuit is used to include general double-plane-iris coupling between waveguides of different cross-sections. A simple loss analysis is included and shows good agreement with measurements. The method is demonstrated for different applications and filter designs based on inductive-septum, inductive-iris and double-plane-iris coupling. Measurements of a 14.2 GHz prototype designed with this technique show close agreement with the specified and predicted performance.

1 Introduction

Synthesis procedures for direct-coupled waveguide filters based on standard filter theory are well documented in the open literature, e.g. [1]. The design techniques involve impedance/admittance inverters to represent the filter coupling sections. Either equivalent-circuit models or, more recently, field-theory-based techniques are used to analyze the effects of the waveguide discontinuities involved [2, 3]. However, two problems are associated with this approach. First, the design specifications, particularly with respect to input return loss performance, are seldom met which requires either post-fabrication fine-tuning or CPU-time intensive optimization procedures. Polynomial curve fitting of accurate results is sometimes applied to avoid extensive optimization [4]. Secondly, double-plane discontinuities including resonant irises and different waveguide dimensions cannot be incorporated with the symmetric inverter circuits used so far.

Therefore, this paper focuses on a fully computer-aided synthesis of direct-coupled waveguide filters including general double-plane-iris coupling between waveguides of different cross-sections. A nonsymmetric inverter circuit and rigorous mode-matching techniques are used for the synthesis of filter dimensions. The final performance is again evaluated by mode-matching techniques. Since this procedure eliminates the need for lengthy optimization routines and/or polynomial curve-fitting calculations, a fully computerized and CPU-time efficient synthesis technique is obtained. Moreover, post-fabrication fine tuning is avoided.

2 Theory

The analysis procedure used to analyze iris and resonator dimensions are based on a modified TE^x_{mn}-mode approach which has been shown to provide excellent results for general double-plane step waveguide discontinuities [5]. The transverse field components in each cross-section (c.f. Fig. 1a)

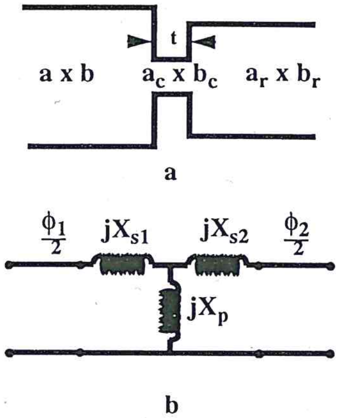

Fig. 1 General iris coupling section between waveguides of different dimensions (a); nonsymmetric inverter circuit (b).

$$E_y = \frac{\partial}{\partial z} A_{hx} \tag{1}$$

$$H_x = \frac{j}{\omega\mu_o}\left[k_o + \frac{\partial^2}{\partial x^2}\right] A_{hx} \tag{2}$$

$$H_y = \frac{j}{\omega\mu_o}\frac{\partial^2}{\partial x \partial y} A_{hx} \tag{3}$$

are derived from the x component of a vector potential

$$A_{hx} = \sum_{q=1}^{Q} \sqrt{\frac{\omega\mu_o/k_{zq}}{A\left[k_o^2 - k_{xm}^2\right]}}\; T_{mn}(x,y) \cdot \left[F_q exp(-jk_{zq}z) - B_q exp(jk_{zq}z)\right] \quad (4)$$

where F_q and B_q are the wave amplitudes travelling in the positive and negative z direction, respectively, and A is the cross-section of the individual region. T_{mn} are the cross-section functions satisfying the boundary conditions. Index q is related to combinations (m,n) which are arranged with respect to increasing cutoff frequencies. For details, the reader is referred to [5] and [6].

The synthesis procedure is based on standard filter theory [1]. Other than in [2], [3], however, a nonsymmetric inverter circuit, as depicted in Fig. 1b, is utilized for the representation of coupling sections. This allows the connection of two different waveguides through a rectangular iris (Fig. 1a) and, therefore, varying resonator cross-sections throughout the filter in general. Reactances X_{s1}, X_{s2}, X_p and electric lengths ϕ_1, ϕ_2 are related to scattering parameters obtained from the mode-matching procedure of (1) - (4).Let S_{mn} with m,n=1,2 be the scattering parameter linking the fundamental modes at both sides of the iris discontinuity in Fig. 1a, then the equivalent-circuit parameters of Fig. 1b are given by

$$jX_{s1} = \frac{[1+S_{11}]\,[1-S_{22}] + S_{21}^2 - 2S_{21}}{[1-S_{11}]\,[1-S_{22}] - S_{21}^2} \quad (5)$$

$$jX_{s2} = \frac{[1-S_{11}]\,[1+S_{22}] + S_{21}^2 - 2S_{21}}{[1-S_{11}]\,[1-S_{22}] - S_{21}^2} \quad (6)$$

$$jX_p = \frac{2S_{21}}{[1-S_{11}]\,[1-S_{22}] - S_{21}^2} \quad (7)$$

$$\begin{bmatrix}\phi_1\\ \phi_2\end{bmatrix} = -\arctan\left\{\frac{X_{s1}+X_{s2}+2X_p}{1-X_{s1}X_{s2}-X_p(X_{s1}+X_{s2})}\right\} \mp \arctan\left\{\frac{X_{s1}-X_{s2}}{1+X_{s1}X_{s2}+X_p(X_{s1}+X_{s2})}\right\} \quad (8)$$

A search algorithm varies the dimensions of the coupling section (a_c/b_c or t) until the inverter values K obtained from field-theory analysis

$$K = \sqrt{\left|\frac{1+\Gamma exp(-j\phi_1)}{1-\Gamma exp(-j\phi_1)}\right|} \quad (9)$$

with

$$\Gamma = \frac{(jX_{s1}+jX_p-1)\,(jX_{s1}+jX_p+1)+X_p^2}{(jX_{s1}+jX_p+1)\,(jX_{s1}+jX_p+1)+X_p^2} \quad (10)$$

are identical to those obtained from filter theory. With ϕ_1 and ϕ_2 determined, the resonator lengths are calculated from [1]

$$l_i = \frac{\lambda_{g0}}{2\pi}\left[\pi + \frac{1}{2}(\phi_{2,i} + \phi_{1,i+1})\right] \quad (11)$$

where ϕ's are usually negative, and λ_{g0} is the resonator's guide wavelength at center frequency. Midband insertion losses can now be estimated according to [1].

The so-obtained entire filter configuration is calculated again by the mode-matching technique which, at this

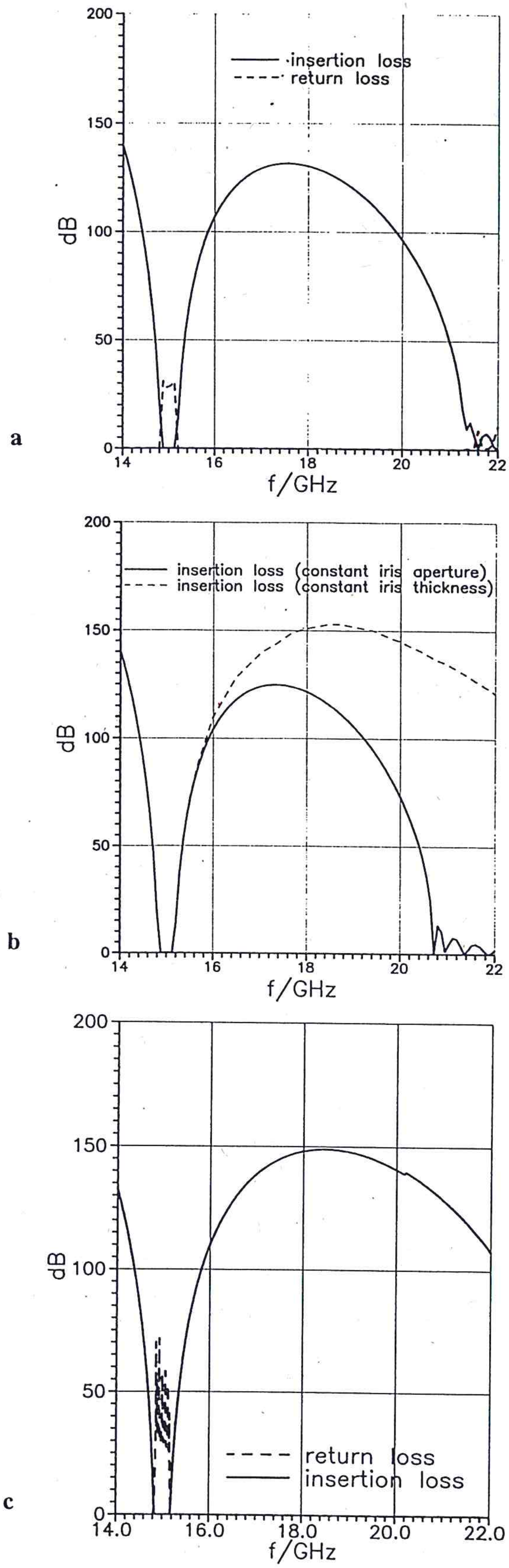

Fig. 2 Performance of different filter configurations synthesized for identical input parameters: standard metal-insert filter (a), inductive-iris filters (b), double-plane-iris filter (c).

time, includes passband losses by considering attenuation constants of all propagating modes over a $\lambda_{g0}/2$ resonator length. If this computed performance deviates from specifications, input parameters are modified accordingly, and the entire procedure is repeated. Since only one design circle is required for many practical applications, the synthesis of one set of filter parameters is usually performed in less than 10 minutes on a 33MHz 486 personal computer.

3 Results.

In order to find the filter configuration offering the best stopband behavior while maintaining in-band specifications, different filter configurations have been synthesized for identical input parameters using this procedure. Figs. 2 show a performance comparison between a standard metal-insert filter (Fig. 2a), inductive-iris filters with variations of constant iris aperture and constant iris thickness (Fig. 2b), and the double-plane-iris filter (Fig. 2c). Since the filters are formed by rectangular TE_{101} resonators, best stopband behavior is achieved by the structure which yields the smallest aperture widths of coupling sections, namely the inductive-iris filter with constant iris thickness (Fig. 2b, dashed line).

A comparison between synthesized and measured responses is shown in Fig. 3. Even though fabrication tolerances of several tenths of micrometers have been measured, close agreement between this synthesis technique and measurements is observed. The general agreement between the mode-matching technique used for the analysis and measurements at double-plane discontinuities is demonstrated in, e.g., [5] and need not be repeated here.

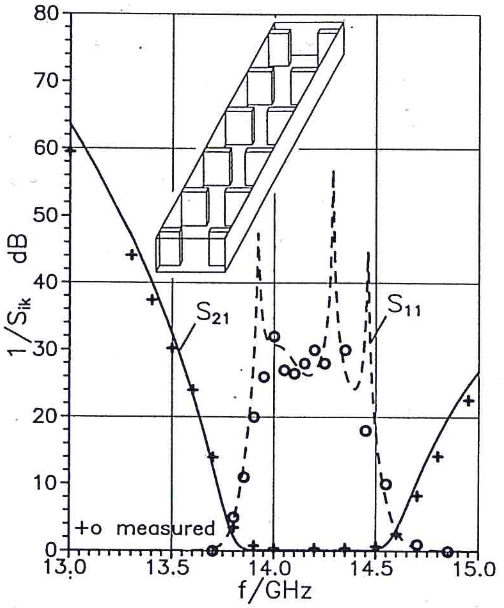

Fig. 3 Comparison between synthesized and measured responses of an inductive-iris filter.

Figs. 4 present synthesis examples involving the new inverter model for general double-plane iris coupling. Ka-band designs within larger (Fig. 4a) and smaller (Fig. 4b) resonator sections are shown for center frequencies at the lower and higher end, respectively, of the waveguide band. The loss approximation used in this mode-matching technique is verified by measurements [7] in Fig. 5. Note that the ordinate is plotted on a 3 dB scale.

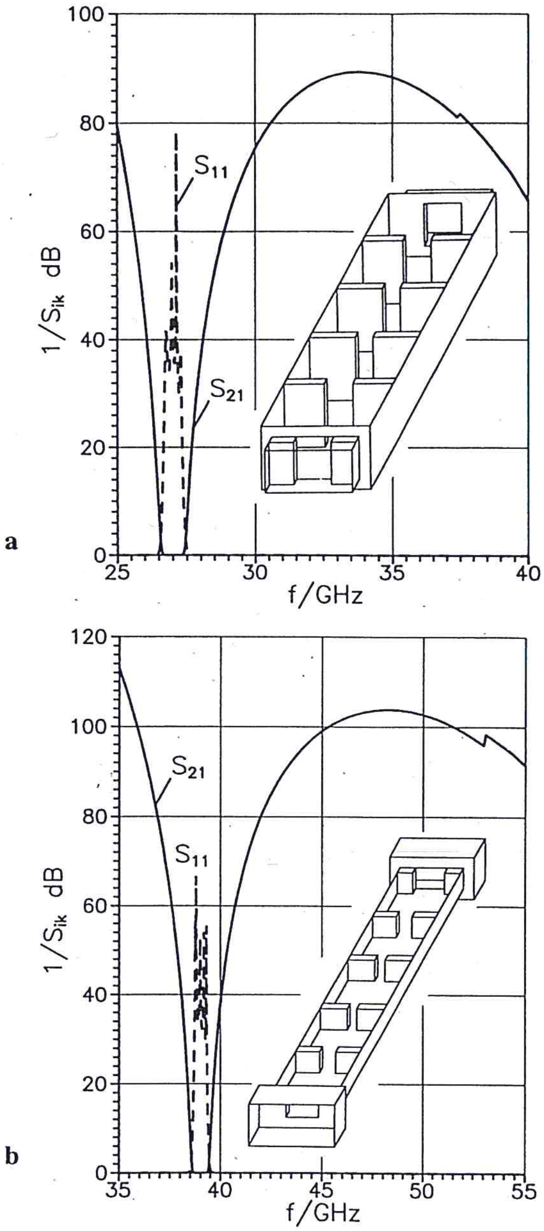

Fig. 4 Performance of synthesized iris filters (600 MHz bandwidth, 30 dB return loss) within a larger (a) and smaller (b) waveguide at 27 and 39 GHz, respectively.

Fig. 6 shows two designs with specifications of 40 db return loss in a 100 MHz bandwidth at 12.5 GHz and 60 dB rejection at ±300 MHz from center frequency. The dashed lines correspond to responses of the conventional inductive-iris filter ($b_r=b$), whereas the solid lines depict the performance of an increased-resonator-height component ($b_r>b$). As expected, the predicted passband losses could be reduced from 0.26 to 0.17 dB by increasing the resonator height. Note that in this example, the synthesis procedure was required to perform three design cycles with modified input specifications in order to simultaneously meet both return loss and rejection specifications. Consequently, some poles move closer together in frequency so that only three instead of six distinct poles are visible in Fig. 6.

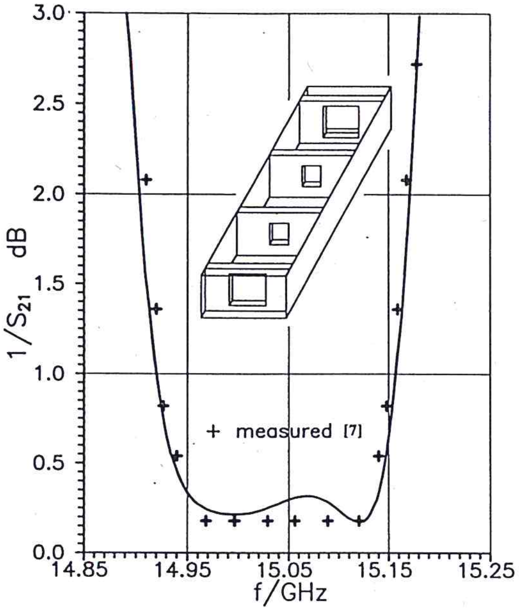

Fig. 5 Calculated (this method) and measured [7] insertion loss of a three-resonator double-plane-iris filter.

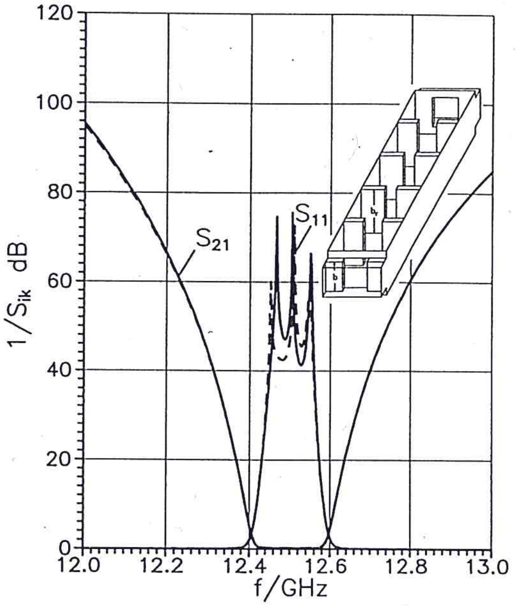

Fig. 6 Responses of synthesized six-resonator filters with standard ($b_r=b$, dashed lines) and increased-height ($b_r>b$, solid lines) resonator dimensions.

4 Conclusions

A computer-aided design procedure for the synthesis of direct-coupled rectangular waveguide bandpass filters is introduced. Standard filter theory involving impedance inverters and an efficient yet rigorous mode-matching technique are combined to synthesize the dimensions of coupling sections and resonators. The nonsymmetric inverter circuit allows general double-plane-iris coupling between waveguides of different cross-sections to be utilized. A simple loss analysis based on the attenuation of propagating modes is incorporated. Hence a highly efficient synthesis procedure is obtained which completely avoids fine optimization and post-fabrication fine tuning. Measured results verify the field-theory-based synthesis procedure. The software is operational on 386 and 486 personal computers.

References

[1] G.L. Matthaei, L. Young and E.M.T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*. Artech House, Dedham 1985.

[2] Y.C. Shih and T. Itoh, "Computer-aided design of millimeter-wave E-plane filters", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp.135-162, Feb. 1983.

[3] L.Q. Bui, D. Ball and T. Itoh, "Broad-band millimeter-wave E-plane bandpass filters", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp.1655-1659, Dec. 1984.

[4] M. Guglielmi, A. Alvarez and G. Gheri, "Multimode synthesis procedure for microwave filters based on thick inductive windows", in *1993 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 447-450.

[5] J. Bornemann and R. Vahldieck, "Characterization of a class of waveguide discontinuities using a modified TE^x_{mn} mode approach", *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 1816-1822, Dec. 1990.

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

[7] U. Tucholke, *Feldtheoretische Analyse und rechnergestützter Entwurf von Resonanzblendenfiltern und Rillenpolarisatoren.* VDI Fortschritt-Bericht, R. 21, Nr. 25, VDI Verlag, Düsseldorf, Germany, 1988.