Low-cost Implementation of a Waveguide-based Microwave Filter in Substrate Integrated Waveguide (SIW) Technology

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Abstract— This paper presents the design and practical implementation of a waveguide-based microwave filter in Substrate Integrated Waveguide (SIW) technology. The use of SIW technology for implementing waveguide filters makes the presented design specially aimed for being used in undergraduate courses related to microwave engineering and filter designing. Their low cost and easiness from the filter fabrication point of view allows their use in microwave laboratory courses where students can implement their own theoretical filter designs and measure their frequency response. The requiring mechanics in the manufacturing of microwave filters in waveguide technology (both rectangular and circular) makes its use practically unfeasible in academic laboratories because of its cost. For this reason, a practical design example of a waveguide iris filter using the impedance inverter model is proposed in this paper for academic laboratories, using SIW technology. This is a low cost and easy to manufacture technology. The overall process includes the design of the ideal band-pass prototype filter using the impedance inverter and its implementation in an inductive iris-coupled waveguide filter, by using a developed electromagnetic simulator based on the mode-matching technique. Finally, the equivalent filter in SIW technology is obtained and optimized by using HFSS simulator, including a SIW to microstrip transition. A prototype of the designed filter has been fabricated and measured, showing a good agreement between measurements and simulations.

1. INTRODUCTION

The Telecommunications Technology Engineering undergraduate program includes, in general, a great number of subjects related to the study and design of microwave filters. A common block to all subjects is usually the design of microwave filters. At low frequencies, such filters can be implemented using lumped elements. However, at higher frequencies (typically in the microwave range), due to the appearance of parasitic effects in lumped elements, such filters are designed by means of distributed parameters, i.e., by transmission line sections. A clear example of transmission line which is especially suitable for the design and practical implementation of microwave filters in a teaching laboratory is the coaxial line, which allows students, starting from a theoretical designed filter obtained in class, to desing and implement a microwave filter with transmission line sections [1]. Alternatively, microstrip technology is also attactive because it is easy to manufacture and low cost, and it allows to incorporate lumped elements of SMT (Surface Mount Technology) in the designed filters. Besides, the measurement of the resulting circuits doesn't need high cost equipment if the working frequency is not too high. For this reason, in the subject *Microwave Technology* [2] several microwave filters have been designed and implemented in microstrip technology by the students, operating in the band of 1 to 5 GHz, under individualized practical sessions. On the other hand, the mechanics required in waveguide-based microwave filter manufacture (in both rectangular and circular waveguide technology) makes it virtually impossible to use it in teaching laboratories for various reasons (cost, high operation frequency...), despite the abundant literature on waveguide-based microwave filter implementation [3]. For this reason, a practical design example of a waveguide iris filter using the impedance inverter model is proposed in this paper for academic laboratories, using SIW technology [4, 5]. In the next section it is described the design process of the ideal band-pass filter prototype using the impedance inverter model, and its implementation in an inductive iris-coupled waveguide filter, by using a developed electromagnetic simulator based on the mode-matching technique [7]. Next, the equivalent filter in SIW technology is obtained and optimized by using HFSS simulator [9], including a SIW to microstrip transition based on a microstrip taper [10] at both ends of the filter. Finally, a prototype of the designed filter has been fabricated and measured, and the measured results are compared to the simulated response.

2. DESIGN AND PRACTICAL IMPLEMENTATION OF THE FILTER IN SIW TECHNOLOGY

In this section we consider the design of a five-pole Chebyshev filter, consisting of several sections of rectangular waveguide coupled with inductive iris, as shown in Fig. 1. Although the filter design has been made in rectangular guide, the ultimate goal of this work is to implement the designed filter in SIW technology, as already mentioned in the introduction, since this technology is low cost and easy to manufacture. This guide is a low cost implementation of the traditional rectangular guide, which takes the advantages of planar lines for easy integration with other circuits, and low radiation losses of the guides. Such guide is constituted by two rows of parallel metallic posts (or via holes) separated a distance a_{SIW} made in a substrate of thickness h metallized on both sides, which delimit the area of propagation of the TE_{10} mode of the SIW guide. The via holes are characterized by a separation s_v and a diameter d_v, whose values are properly chosen to avoid radiation losses [4], so as to fulfill the following conditions:

$$d_v < \lambda_g/5, \quad s_v \leq 2d_v \tag{1}$$

where λ_g is the guided wavelength. On the other hand, the propagation constant of this guide is determined by the width a_{SIW} of the SIW and by the substrate permittivity ϵ_r. A previous study of this type of guide [6] demonstrates that a SIW can be analyzed as an equivalent rectangular waveguide of effective width a given by:

$$a = a_{SIW} - \frac{d_v^2}{0,95s_v} \tag{2}$$

Therefore the final design of the equivalent filter in SIW technology has been accomplished using Eq. (2) in each of the respective sections of rectangular waveguide.

For the design of the waveguide-based filter, the equivalent circuit model of impedance inverters of an inductive waveguide iris through a T network [3] has been employed, as it can be seen in Fig. 2(a). The filter consists of half-wave resonators separated by inductive iris. Using an electromagnetic simulator, the iris scattering matrix can be obtained and therefore its equivalent T network. The model has been combined with an electromagnetic simulator based on the mode-matching technique [7] to calculate the physical dimensions of the filter. Each iris is represented by two series reactances denoted by X_s and a shunt reactance denoted by X_p. The equivalent circuital rectangular iris filter is shown in Fig. 2(a). In order to transform it in the impedance inverters model, we use the impedance inverter circuit consisting of an inductive T network and two sections of length $\varphi/2$ on each side. The inverter is created by adding a length $\varphi/2$ and $-\varphi/2$ on each side of the discontinuity, as shown in Fig. 2(b). In this case the resonators are transmission lines of length L_n connected to two transmission lines of artificial lengths $-\varphi_n/2$ and $-\varphi_{n+1}/2$. These lengths represent the load of the resonator from the adjacent coupling inverters. The specifications of the designed filter, whose scheme is shown in Fig. 1, are the following: it is a band-pass Chebyshev filter of 5th order with a center frequency $f_0 = 4$ GHz, a bandwidth of 600 MHz and return loss

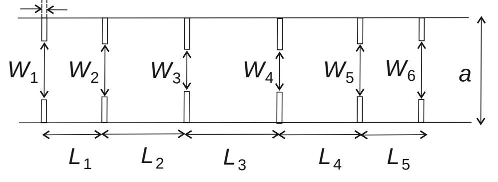


Figure 1: Top view of a 5th order inductive rectangular waveguide filter.

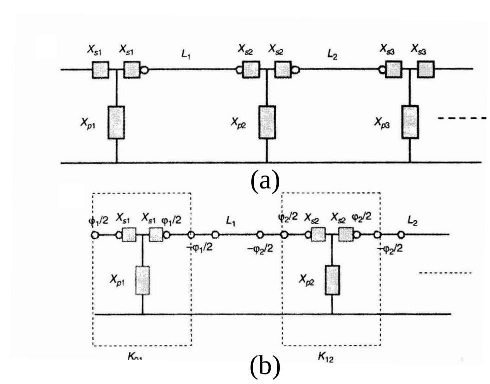


Figure 2: (a) Equivalent circuit model of an inductive waveguide iris through a T network. (b) Equivalent impedance inverters model of an inductive waveguide iris through a T network.

of $RL = 15\,\text{dB}$ (equivalent to a 0.1 dB ripple in the passband). The rectangular waveguide has a width of $a = 15.8\,\text{mm}$ and a height of $b = 0.63\,\text{mm}$, corresponding to the thickness $b = h$ of the employed substrate, which in our case is a Taconic CER-10 substrate whose $\epsilon_r = 10$ and $\tan(\delta) = 0.0035$ [8], double-sided metallized with a copper film 20 μm thick. Iris in all cases have a thickness of $t = 3\,\text{mm}$.

The coefficients of a 5th order Chebyshev low-pass filter with $RL = 15\,\text{dB}$ are [3]: $g_0 = 1$, $g_1 = g_5 = 1.1468$, $g_2 = g_4 = 1.3712$, $g_3 = 1.9750$. The filter center frequency and band-edge frequencies are related by:

$$f_0 = \sqrt{f_1 f_2}, \quad BW = f_1 - f_2, \tag{3}$$

which give $f_1 = 3.7\,\text{GHz}$, $f_2 = 4.3\,\text{GHz}$. The filter relative bandwidth is:

$$\Delta = \frac{\lambda_{g1} - \lambda_{g2}}{\lambda_{g0}} = 0.3636 \tag{4}$$

Then, the values obtained for the impedance inverter factors are:

$$\frac{K_{01}}{Z_0} = \frac{K_{56}}{Z_0} = \sqrt{\frac{\pi\Delta}{2g_0 g_1}} = 0.7051 \tag{5}$$

$$\frac{K_{12}}{Z_0} = \frac{K_{45}}{Z_0} = \frac{\pi\Delta}{2\sqrt{g_1 g_2}} = 0.45546 \tag{6}$$

$$\frac{K_{23}}{Z_0} = \frac{K_{34}}{Z_0} = \frac{\pi\Delta}{2\sqrt{g_2 g_3}} = 0.34706 \tag{7}$$

Using an electromagnetic simulator based on the mode matching technique [7], one can calculate the scattering parameters of a rectangular iris (referred to the discontinuity planes), which are related to the T network elements shown in Fig. 2(a), X_s and X_p by the following equations [3]:

$$j\frac{X_s}{Z_0} = \frac{1 - S_{12} + S_{11}}{1 - S_{11} + S_{12}} \tag{8}$$

$$j\frac{X_p}{Z_0} = \frac{2S_{12}}{(1 - S_{11})^2 - S_{12}^2} \tag{9}$$

where S_{11}, S_{21} and S_{12} are the scattering parameters of the TE_{10} fundamental mode of the input waveguide at the filter center frequency f_0. For the impedance inverter shown in Fig. 2(b), X_s and X_p are related to K/Z_0 and φ by:

$$\frac{K}{Z_0} = \left|\tan\left(\frac{\varphi}{2}\text{atan}\frac{X_s}{Z_0}\right)\right| \tag{10}$$

$$\varphi = -\text{atan}\left(2\frac{X_p}{Z_0} + \frac{X_s}{Z_0}\right) - \text{atan}\frac{X_s}{Z_0} \tag{11}$$

The scattering parameters of several iris of different width have been obtained, ranging from 1 to 15 mm, providing the curve shown in Fig. 3 in which the impedance inverter factor K/Z_0 is

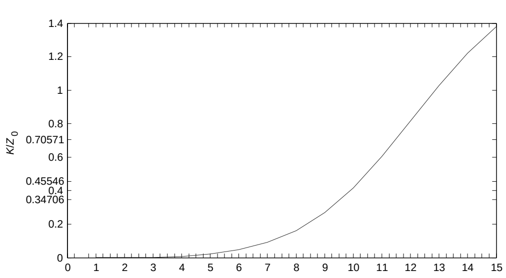


Figure 3: Impedance inverter factor $\frac{K}{Z_0}$ as a function of the width (W) of the rectangular waveguide iris.

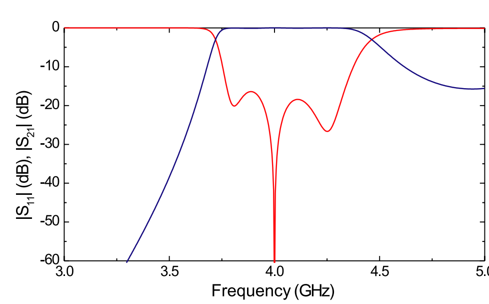
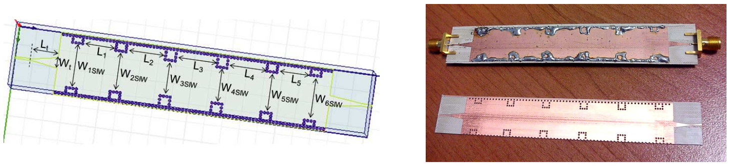


Figure 4: Electrical response of the designed rectangular waveguide filter.



(a) (b)

Figure 5: (a) Scheme of the designed filter in SIW technology. (b) Photograph of the fabricated filter.

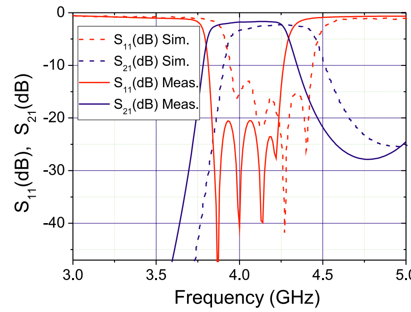


Figure 6: Simulated and measured response of the designed filter in SIW technology.

represented as a function of the iris width W. From the curve represented in Fig. 3, and the values of the inverter factors provided by Eqs. (5)–(7), the following values of the iris widths have been deduced for our filter: $W_1 = W_6 = 12.4\,\mathrm{mm}$, $W_2 = W_5 = 10.65\,\mathrm{mm}$, $W_3 = W_4 = 9.85\,\mathrm{mm}$. For these values of iris widths, the values of the phases provided by Eq. (11) are: $\varphi_1 = \varphi_6 = -1.7\,\mathrm{rad}$, $\varphi_2 = \varphi_5 = -1.28\,\mathrm{rad}$, $\varphi_3 = \varphi_4 = -1.07\,\mathrm{rad}$. Finally, the resonator lengths are given by the following equation:

$$L_n = \frac{\lambda_{g0}}{2\pi}\left[\pi + \frac{1}{2}\left(\varphi_n + \varphi_{n+1}\right)\right], \quad n = 1, \ldots, N \tag{12}$$

The obtained phases yield the following values of the resonator lengths: $L_1 = L_5 = 9.4\,\mathrm{mm}$, $L_2 = L_4 = 11.2\,\mathrm{mm}$, $L_3 = 11.8\,\mathrm{mm}$. In Fig. 4 it is shown the simulated response of the designed filter using the mode-matching technique. In this figure it can be seen that the designed filter meets the design specifications.

The next step in the design process is to obtain the equivalent waveguide widths in SIW technology, and de design of the microstrip to SIW transition. To this end, the following parameters for the via holes have been employed: $d_v = 0.7\,\mathrm{mm}$, $s_v = 0.95\,\mathrm{mm}$. With the equivalence given by Eq. (2), the widths of the different sections of SIW waveguide can be obtained. On the other hand, for the microstrip to SIW transition, the same transition presented in [10] has been implemented, consisting of a microstrip taper (see Fig. 5(a)). Such transition provides a wide bandwidth and can be designed to cover the entire operation band of the proposed filter. Finally, an optimization process of the designed filter response has been performed through HFSS simulator, providing the following final filter parameters: $W_{1SIW} = W_{6SIW} = 11.86\,\mathrm{mm}$, $W_{2SIW} = W_{5SIW} = 10.48\,\mathrm{mm}$, $W_{3SIW} = W_{4SIW} = 9.90\,\mathrm{mm}$, $L_1 = L_5 = 9.4\,\mathrm{mm}$, $L_2 = L_4 = 11.2\,\mathrm{mm}$, $L_3 = 11.8\,\mathrm{mm}$. The dimensions of the width and length of the taper transition are 2.60 mm and 7.08 mm respectively, while the microstrip line width is of 0.6 mm.

In Fig. 5(a) it is represented a scheme of the designed SIW filter with its final dimensions, while a photograph of the fabricated filter is shown in Fig. 5(b) (before and after metallizing the via holes). Finally, the simulated response of the designed filter in SIW technology is shown in Fig. 6 with dashed line, including the effect of conductor and dielectric losses. In this figure it is also represented with solid line the measured response of the filter with an Agilent vectorial network analyzer. The measured response shows a good impedance matching in the passband (better than 12.5 dB) and also a good out of band rejection performance (better than 20 dB). Although the measurements and simulations show the same bandwidth, a frequency shift of 100 MHz is observed, which may be caused by a lower value of the relative permittivity of the employed substrate.

3. CONCLUSION

A practical design example of a waveguide iris filter using the impedance inverter model is proposed in this paper for academic laboratories, using SIW sections as a low-cost and easy to manufacture technology. An example of a band-pass filter centered at 4 GHz has been designed, optimized and fabricated to show all the design and fabrication process, showing a good agreement between measurements and simulations.

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