GENERIC MICROSTRIP STRUCTURE FOR THE REALIZATION OF ALL-TYPE BROADBAND FILTERS

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ABSTRACT: *A generic microstrip structure is used for the design of all-type broadband filters, based on the analogy between wave and transmission line theories. A Matlab-based lumped (LC) and scattered (microstrip line) filter design tool is developed for the automation of the filter design. Sample lowpass, highpass, bandpass, and bandstop filters are designed and their operational characteristics are validated via in-house prepared FDTD-based virtual microstrip circuit simulator.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 2390–2393, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21975

Key words: *microstrip; filter design; analog filters; lowpass; highpass; bandpass; bandstop; lumped element circuits; FDTD; Matlab*

1. INTRODUCTION

Lumped element broadband filter design theory has become a classical part of both circuit and transmission line theories. The principle design steps can be found even in many undergraduate lecture notes [1]. On the other hand, microwave filter design based on waveguides, cavities, and microstrip circuits necessitates scattered parameter approach, has been a research topic for many decades, and still remains of great importance in the development of microwave networks [2, 3].

Currently, microstrip filter design approaches may basically be grouped into two: (i) Some start with full wave electromagnetic equations and use powerful time and frequency domain simulators, such as the finite difference time domain (FDTD), transmission line matrix, finite element (FE), method of moments (MoM), etc. (ii) others use the analogy between electromagnetic wave and circuit (transmission line) theories [4].

In this article, a generic microstrip structure is used for the design of different types of filters and is extended up to the fifth order [2]. A Matlab-based filter design virtual tool (VT) MS_FILTER is prepared to automate the design. Any type of a filter may be selected by the user together with the filter specifications, the frequency band, center frequency, and the desired attenuation. The VT then calculates the order of the filter, specifies element values of the lowpass prototype, and lumped (LC) element filter is designed by specifying the values of every inductance and conductance. Finally, the dimensions of the microstrip generic structure are calculated by using the analogy between wave and circuit theories according to the user-selected relative permittivity and height of the substrate. The full-wave FDTD-based MSTRIP [3] is used for the validations via comparisons of the designed lumped element and microstrip filters.

2. ANALOG (LUMPED ELEMENT) FILTER THEORY

Analog filter design is based on cascading a number of inductances (L) and capacitors (C) in a way to supply user specified frequency and attenuation characteristics. The impedances of an inductor and capacitor are $Z_L = j\omega L$ and $Z_C = -j(\omega L)^{-1}$, respectively, which show that a serially (parallel) connected inductor (capacitor) between input and output of a 2-port circuit acts a low (high) pass filter and a vice versa. Also, a serial (parallel) connected LC circuit presents impedance minimum (maximum) at the resonance frequency of $f_C = (2\pi\sqrt{LC})^{-1}$; therefore, these resonance circuits also act as low or high pass filters depending on their serial or parallel insertion between input and output. As the number of LC pairs with suitably-specified element values (i.e. the order of filter) increases the filter band broadens. These characteristics form the basis of analog filter theory, and although become classic, the two well known analog filter design approaches are briefly included here for the sake of completeness.

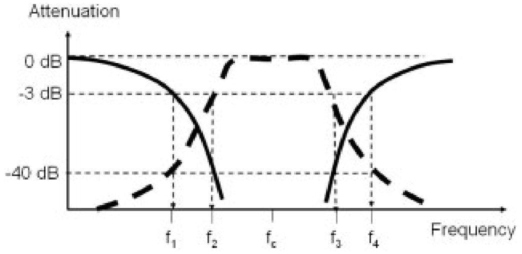


Figure 1 Four types of filter characteristics and required parameter

Figure 1 illustrates characteristics of four different types of filters. The specification of the 3 dB cut-off frequency f_1 and the desired out of band attenuation at f_2 are enough to design a lowpass filter (LPF). The center frequency f_c, the passband $B = f_4 - f_1$, and maximum attenuation at f_2 and f_3 should be specified for the bandstop filter (BSF) design. The specification of the 3 dB cut-off frequency f_4 and the desired out of band attenuation at f_3 are the design parameters of a highpass filter (HPF). Finally, the center frequency f_c, the passband $B = f_3 - f_2$, and maximum attenuation at f_1 and f_4 should be specified for the bandpass filter (BPF) design.

Two of the widely used analog filter design methods are the Butterworth and Chebychev approaches [1]. Butterworth filters satisfy the desired amplitude response without ripples inside the passband, while Chebychev filters yield steeper initial descent outside the band, but the payoff is the undesired ripples inside the passband.

The design parameters for the Chebychev filters are the cut-off (or center) frequency, maximum permissible ripple in the passband R_{dB} and the attenuation at a given frequency beyond the passband, A_{dB}. The order of the filter is specified from these two parameters via:

$$A_{dB} = 10\ \mathrm{Log}_{10}(1 + \Delta C_n^2(\chi')), \tag{1}$$

$$\chi' = \chi \cosh\left(\frac{1}{n}\cosh^{-1}\left(\frac{1}{\Delta}\right)\right), \qquad \Delta = \sqrt{10^{R_{dB}/10} - 1}, \qquad \chi = \left(\frac{f_2}{f_1}\right), \tag{2}$$

once the frequencies f_1 and $f_2$of the LPF, the ripple R_{dB}, and the order of the filter are specified. Here, n is the filter order and $C_n^2(\chi)$ are the Chebychev polynomials, the first four of which are χ, $2\chi^2 - 1$, $4\chi^3 - 3\chi$, $8\chi^4 - 8\chi^2 + 1$, and the generic form is $C_n(\chi) = 2\chi C_{n-1}(\chi) - C_{n-2}(\chi)$. Although n may be anything and gets higher and higher as the filter band and out of band attenuation increases, usually it is between $3 \leq n \leq 5$ in practical microwave filters. A fourth order Chebychev filter, for example, supply

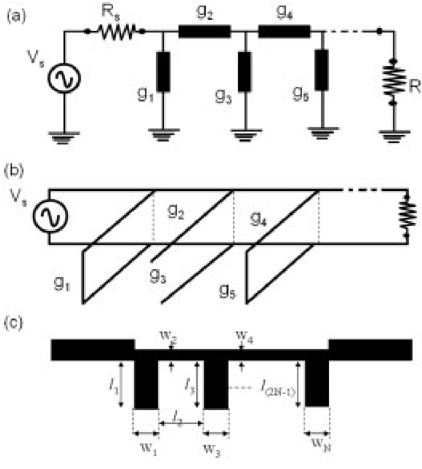


Figure 2 Analog LC LPF prototype and the generic microstrip structure

more than $A_{dB} \geq 47dB$ dB attenuation if maximum allowable ripple in the passband is $R_{\mathrm{dB}} = 2/5dB$ and $f_1/f_c = 2.5$.

The equations of the Butterworth filters which relates out of band attenuation A_{dB} and the order of filter are

$$A_{dB} = 10\ \mathrm{Log}_{10}(1 + \chi^{2n}), \tag{3}$$

$$n = \frac{1}{2}\frac{\mathrm{Log}_{10}(10^{A_{dB}/10} - 1)}{\mathrm{Log}_{10}(\chi)}, \tag{4}$$

with the same χ given in Eq. (2). The actual design procedure is nothing but supplying these two filter characteristics. The first step is to predict the order of the LPF prototype, which has a source impedance of $R_S = 1\Omega$ and a cutoff frequency of $f_1 = 1$. The LPF prototype can be converted into any of the highpass, bandpass, or bandstop prototypes by using the frequency and impedance scaling.

Here, Butterworth type filter design is taken into account. Once the order of the filter is specified, the generic elements of the LPF prototype can be calculated from

$$g_k = 2\ \mathrm{Sin}\frac{(2k-1)\pi}{2n},\ k = 1,2,\cdots,n, \tag{5}$$

as shown in Figure 2. The elements g_k of the second order LPF are $g_1 = g_2 = 1.414$, but are $g_1 = 1.0$, $g_2 = 2.0$, $g_3 = 1.0$ for the third order LPF. Like the Chebychev filter, a fourth order Butterworth filter also supplies more than $A_{dB} \geq 47dB$ dB attenuation if $\chi = f_2/f_1 = 2.5$.

Usually, the order of filter is left to the designer and the customer is only interested in the operational frequencies, the attenuation, therefore one has to use (1) for Chebychev and (4) for Butterworth filters and solve for the order. This was too complex in the past when there were no computers so charts of attenuation vs. frequency were used to determine the order of the filters. The design of the LPF filter is completed once the order of the filter is calculated since prototype values may directly be taken from pre-prepared tables. The real LC element values of the filter can then be calculated via transformation/scaling equations [1]. For example, these equations for the real LPF are

$$C = \frac{C_n}{2\pi f_1 R_L}[F], \tag{6a}$$

$$L = \frac{R_L L_n}{2\pi f_1}[H], \tag{6b}$$

if source and load resistors are equal. Here, L_n and C_n are the elements values of the prototype, f_1 is the cut-off frequency, and R_L is the load resistor. Any other filter may directly be obtained from the LPF–HPF, LPF–BPF, or LPF–BSF transformation equations [1] (it should be noted that $\chi = f_2/f_1$ in Eq. (2) should be replaced with $\chi = f_2/f_1$, $\chi = (f_4 - f_1)/(f_3 - f_2)$, and $\chi = (f_3 - f_2)/(f_4 - f_1)$ for HPF, BPF, and BSF, respectively).

3. MICROSTRIP FILTER DESIGN

Lumped (LC) element filters mostly work at low frequencies. Circuit elements such as inductors and capacitors are available only for a limited range of values and are difficult to implement at microwaves. Also electrical effects of element seals, connection wires, jumper lengths, etc. are no longer negligible at microwave frequencies. Therefore, scattered parameters approach and the transmission line (TL) theory are used in filter design at microwaves. It is well known that any inductance and/or capacitor value can be obtained as the input impedance of a finite-length, short circuited (SC) or open circuited (OC) transmission line, since $Z_{in} = -jZ\tan(\beta l)$ and $Z_{in} = jZn_0\,\mathrm{cotg}(\beta l)$, where Z_0 and l are the characteristic impedance and length of the TL, respectively. These equations are used to calculate the characteristic impedances of the stubs of the TL-based filters. Figure 2 illustrates the generic analog filter structure and its TL implementation.

Microwave filters are mostly integrated on a printed board with other system circuits and elements, therefore microstrip lines are the basic filter elements at microwaves. One design approach is to use Richard's transformations coupled with Kuroda four identities [2], which allows realization of the lumped element filter prototypes in terms of OC or SC TL stubs [4]. Richard's transformations convert series inductors to series stubs, and shunt capacitors to shunt stubs since microstrip line implementation of the series stubs is extremely difficult. Kuroda identities are used to convert these to shunt stubs [5].

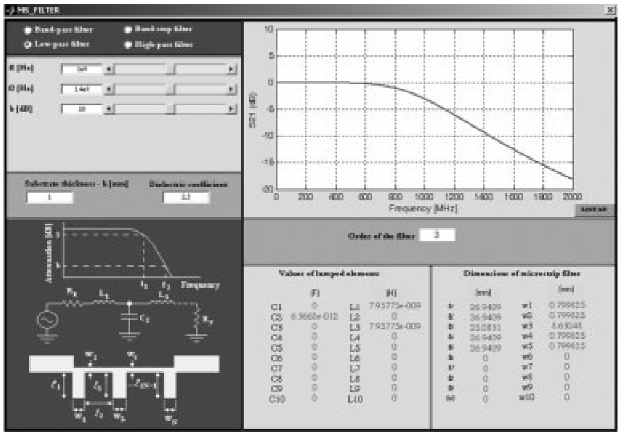
Richard's transformation is used in the implementation of LPF prototype at microwaves. With this transformation, a LPF prototype can be transformed into its TL equivalent LPF prototype [see Fig. 2(b)]. According to Richard's transformation, a capacitor can be replaced with a parallel OC stub and a series inductor can be replaced with a SC stub. The lengths of these stubs should be $\lambda/8$ (where λ is the wavelength) at the cutoff frequency.

At microwaves, BPF and BSF require elements that behave as series or parallel resonant circuits. Therefore, BPF and BSF prototypes can be realized using $\lambda/4$-long TL resonators. A parallel resonator circuit of lumped element filter prototype can be replaced with a SC stub [3, 5]. On the other hand, a series resonator in BSF prototype can be replaced with an OC stub at microwave frequencies.

The generic microstrip filter structure is also pictured in Figure 2. The generic filter has three-stubs and two-interconnects between input and output. The widths of interconnects and the lengths of OC or SC stubs depends on the type of the filter. Apparently, this is a third order filter, but may be extended up to the fifth order when Kuroda identities [2] are used accordingly.

In summary, filter design approach may be listed as follows:

- First, the order of analog filter is calculated from user-specified filter characteristics,



Values of lumped elements

	[F]		[H]
C1	0	L1	7.95775e-009
C2	6.3662e-012	L2	0
C3	0	L3	7.95775e-009
C4	0	L4	0
C5	0	L5	0
C6	0	L6	0
C7	0	L7	0
C8	0	L8	0
C9	0	L9	0
C10	0	L10	0

Dimensions of microstrip filter

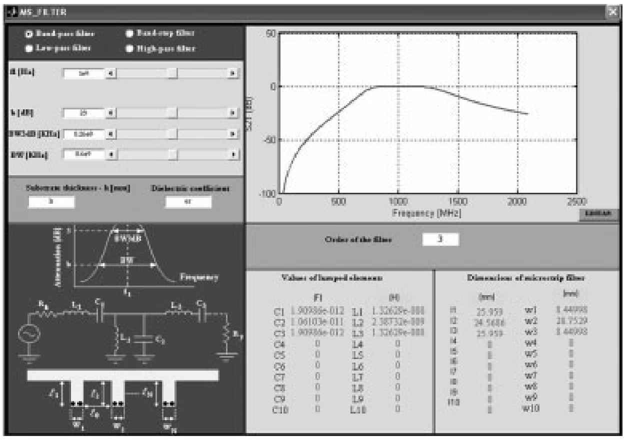
	[mm]		[mm]
l1	26.9409	w1	0.799825
l2	26.9409	w2	0.799825
l3	23.0831	w3	3.63048
l4	26.9409	w4	0.799825
l5	26.9409	w5	0.799825
l6	0	w6	0
l7	0	w7	0
l8	0	w8	0
l9	0	w9	0
l10	0	w10	0

Figure 3 The front panel of the Matlab-based MS_FILTER virtual tool and a sample LPF design (the cut-off frequency is $f_c = 1$ GHz, required attenuation at $f_2 = 1.4$ GHz is 10 dB)

- The elements of the prototype LPF are determined [Fig. 2(a)],
- The LPF–HPF, LPF–BPF or LPF–BSF transformation is done if any other type of a filter is desired,
- The real LC elements are calculated via scaling equations,
- The TL equivalent of the filter is designed via Richard's transformation and Kuroda identities, and characteristic impedances and lengths of TL stubs are specified [Fig. 2(b)],
- Finally, microstrip stub lengths and widths are calculated [Fig. 2(c)] by using [2]

$$W/h = \begin{cases} \dfrac{8e^A}{e^{2A}-2} & W/h < 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\right. & \\ \left.\left\{\ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r}\right\}\right] & W/h > 2 \end{cases} \tag{7a}$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_{r-1}}{\varepsilon_{r+1}}\left(0.23 + \frac{0.11}{\varepsilon_r}\right), \quad B = \frac{377\pi}{2Z_c\sqrt{\varepsilon_r}}. \tag{7b}$$



Values of lumped elements

	[F]		[H]
C1	1.90986e-012	L1	1.32629e-008
C2	1.06103e-011	L2	2.38732e-009
C3	1.90986e-012	L3	1.32629e-008
C4	0	L4	0
C5	0	L5	0
C6	0	L6	0
C7	0	L7	0
C8	0	L8	0
C9	0	L9	0
C10	0	L10	0

Dimensions of microstrip filter

	[mm]		[mm]
l1	25.959	w1	1.44998
l2	24.5686	w2	18.7529
l3	25.959	w3	1.44998
l4	0	w4	0
l5	0	w5	0
l6	0	w6	0
l7	0	w7	0
l8	0	w8	0
l9	0	w9	0
l10	0	w10	0

Figure 4 A sample BPF design with the Matlab-based MS_FILTER virtual tool (the center frequency is $f_c = 1$ GHz, bandwidth is $B = 600$ MHz, and the required attenuation at $f_1 = 700$ MHz and $f_4 = 1300$ MHz is 25 dB)

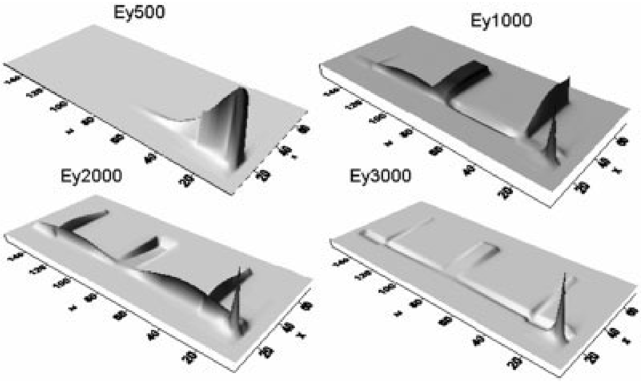


Figure 5 Three-dimensional plots at different time instants recorded during the FDTD simulations for a sample LPF design

4. THE MATLAB FILTER DESIGN PACKAGE

The MATLAB virtual tool MS_FILTER has been prepared for both LC and microstrip filter design [4, 5]. The front panel of the tool is shown in Figure 3. A pop-up menu at top-right is reserved for the selection of any of LPF, HPF, BPF, or BSF types. Once the user specifies the filter type the frequency characteristics, its LC prototype, and the microstrip line prototype appear at bottom-left. Filter characteristics and microstrip line substrate specifications (dielectric thickness and relative permittivity) are supplied by the user either from the data boxes or by using the sliding bars. The output data of the designed filter is given at bottom-right. Here, the order of the filter, values of LC elements, and the dimensions of the microstrip line prototype filter are given at this section. The graph at top-right is for the frequency response of the designed filter. The transfer function vs. frequency (either in linear or logarithmic scale) is given in this window. A third order LPF example is designed in this figure with a cut-off frequency of $f_c = 1GHz$ and 10db attenuation at $f_2 = 1.4GHz$. The analog filter elements are found to be $L_1 = 7.96nH$, $C_2 = 6.37pF$, and $L_3 = 7.96nH$. The TL widths and lengths of the generic filter are as given in the front panel.

An example of a BPF design is presented in Figure 4. Here, a 600 MHz passband around the center frequency of 1 GHz is requested. The out of passband attenuation is specified to be 25 dB at $f_1 = 700$ MHz and $f_4 = 1300$ MHz. The three series resonance circuit elements of the analog filter elements are found to be $L_1 = 13.2nH$, $C_1 = 1.91pF$, $L_2 = 2.39nH$, $C_2 = 10.6pF$ and $L_3 = 13.2nH$, $C_3 = 1.91pF$. The TL widths and lengths of the generic filter are as given in the front panel. It should be noted thatthe stubs are SC via thin pins as observed in the figure. Although this is easily achieved in the simulations, SC pins are extremely difficult to realize in practice.

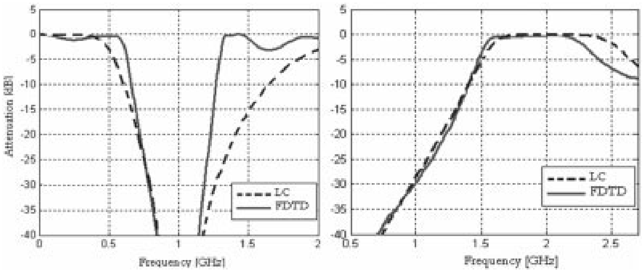


Figure 6 BSF and BPF designed with MS_FILTER virtual tool and analyzed via the FDTD-based MSTRIP package

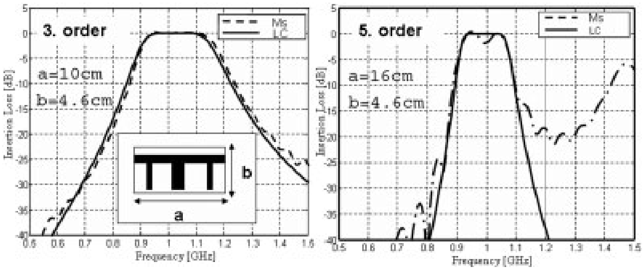


Figure 7 Comparisons of third and fifth order BPF designed with MS_FILTER and analyzed via MSTRIP

The design method in the MS_FILTER is based on wave–circuit theory analogy and as mentioned in Ref. 1 as well as in Ref. 2. This approach works well up to a few GHz (i.e., at most 3–4 GHz) frequencies. To illustrate this, filters designed with MS_FILTER are validated against the FDTD-based full wave in-house prepared MSTRIP simulator [3]. MSTRIP is prepared for both educational and research purposes. The beauty of this microstip circuit simulator resides on the fact that the user easily designs a circuit on top of single or double layer dielectrics by using PC mouse and visualizes the wave scattering underneath the microstrip circuit in the dielectric layer directly on time. An example of this visualization is given in Figure 5. Here, vertical component of the pulsed electric field underneath the microstrip circuit during the FDTD simulations at different time instants are plotted. The user may observe the pulse excitation, its scattering along the main line as well as the stubs.

Two examples that belong to the comparisons of MS_FILTER and MSTRIP simulations are given in Figure 6; on the left for the BSF and on the right for the BPF designs, respectively.

As mentioned above, the use of the same generic mictrostrip structure is extended up to fifth order filters. An example is illustrated in Figure 7 where MS_FILTER and MSTRIP results are compared on third (left) and fifth (right) order BPF, respectively. As observed, although passband specifications are satisfied unwanted ripples appear as the frequency increases for the fifth order BPF.

Finally, this fifth order filter is fabricated, scattering parameters are measured, and the results are compared against the simulation data. Figure 8 shows this comparison as attenuation vs. frequency with the photograph of the fabricated filter as the inset.

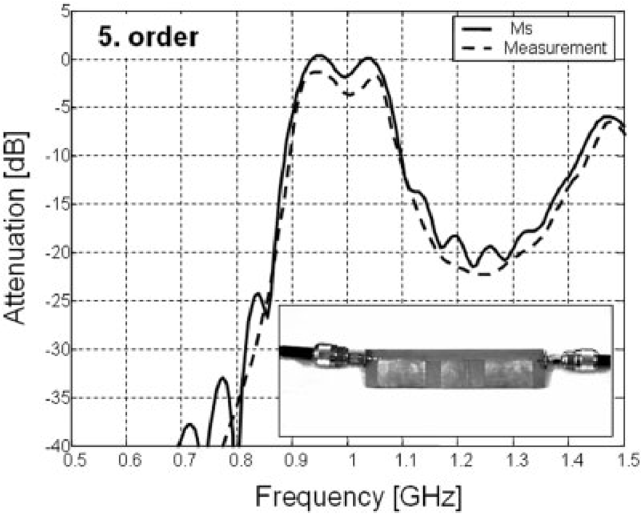


Figure 8 A comparison of the simulation results against measurement

5. CONCLUSION

The analogy between lumped and scattered parameter representations can be used in filter design. A Matlab-based filter design virtual tool that can be used for both engineering and educational purposes is developed. Any of the four types of filters with the desired band and attenuation characteristics is chosen first. The virtual tool designs the lumped LC element filter and converts it into a microstrip line filter. The same generic microstrip structure is used for all four types of filters where specified characteristics are satisfied only by adjusting the widths and lengths of main line and the stubs.

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A RADIATOR ELEMENT FOR ACTIVE PHASED ARRAY ANTENNA

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ABSTRACT: *This paper is concerned with selection and design of an antenna element of a phased array antenna for 20 GHz communications satellite. For this purpose, a new type of dual-mode horn with inner choke ring at the excitation region is proposed. Also, measured results compared with predicted data for the dual-mode horn radiator with a circular polarizer are presented.* © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 48: 2393–2395, 2006; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.21971

Key words: *antenna; horn; phased array antenna; polarizer*

1. INTRODUCTION

This paper mainly concerns an antenna element of a phased array antenna (PAA) for a 20 GHz communications satellite. One of the most important stages of PAA design for a communications satellite is the right antenna element choosing. Some key issues of the requirements are reliability, weight, and volume. For this, horn radiators were previously used for the antenna element. However, for a PAA of a communications satellite, there are many restrictions to the selection of the