FILTERING ANTENNAS: SYNTHESIS AND DESIGN

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Abstract - ***A new co-design approach is used to synthesize and design the new printed Bandpass Filtering Antenna. For the purpose of miniaturization and enhancing the overall performance of the circuit, a multifunction module is designed. It performs filtering and radiating, simultaneously with the help of co-design approach. A detailed synthesis and design procedure is given of two types of filtering antennas. Type 1 is 2.45 GHz third-order Chebyshev Bandpass filtering antenna, which provides better design accuracy and performance as compared to conventional bandpass filter. The parallel coupled microstrip lines and inverted-L antenna is used to synthesize and design. Type 2 is 5.2 GHz second order Chebyshev Bandpass filtering antenna, which provides quasi-elliptic broadside antenna gain response. A U-shape radiating patch is excited by a T-shape resonator through an inset coupling structure for the purpose of synthesis and design. .***

Key Words: *Chebyshev Bandpass Filter; Filtering Antenna; Filter synthesis; quasi-elliptic function bandpass filter.*

1. INTRODUCTION

Microwave communication system is developing very prosperously, which corresponds to need of low-cost, compact and highly efficient systems. In almost all wireless communication systems, antenna is a necessary component for transmitting or receiving microwave signals along with bandpass filters for suppressing unwanted spurious signals. The impedance mismatch between the individually designed antenna and filter causes interference, increases insertion loss and thus affecting the performance of the circuit. Integration of two or more functions together leads to multifunction module miniaturizing the circuit size and leading to improved circuit performance. Since radiating and filtering are the most important functions of the communication system, integrating these functions into a single module will reduce the additional circuit and enhance the overall performance of the circuit. This single module is Filtering Antenna, performing both the functions simultaneously. Filtering Antenna provides shaping of frequency response [1], [2], [12]. Conventionally, these two components are designed separately and connected by a section of 50-Ω transmission line. This line may not be matched perfectly within the whole frequency range in interest, so the transmission-line section forms a resonator at some frequency and causes interference. The extra line not only degrades the performance of the system, but also occupies the additional circuit area. In addition, polarization purity is one of the important issues for antenna design [2].

Many efforts have been carried out in past for synthesis and designing of Filtering Antenna [3]-[8]. In [3], filtering function was integrated in an electromagnetic horn. But standard method was not followed and also cross polarisation was slightly detorioted. In [4], cavities were created in leaky waveguide so as to control the bandwidth and hence, develop the filtering function. This design did not consider the filter's or antenna's specifications. In [5], to control the bandwidth of antenna, the bandpass filter was directly inserted at the feed point of patch antenna. But they faced problems in mounting of two structures together along with less controlled bandwidth and low radiation efficiency. In [6], Co-design approach was used to enhance the performance parameters of the circuit. 3-pole compact CPS structure is used as a filter, while CPS fed loop is used as an antenna and both are designed by co-design approach. The frequency response was not as per the expectations. In [7], multilayered (ceramic/foam) technology resulting in the composite structure made of high and low permittivity layers was used. But such a complicated design led to various design constraints. In [8], a single material technology was used and co-design approach was used for integrating 3rd order filter with microstrip antenna which uses same substrate for both. However, for all the analysis and designing, only the centre frequency was considered and not the entire bandwidth. Also circuit and antenna losses were not considered. But, Type 1 design considers the entire bandwidth and hence, gives better results.

The filtering antennas were achieved by different forms, such as circular patch antennas [9], slot dipole antennas [10], monopolar antennas [11], and rectangular patch antennas [5], [12]. But, Type 2 design the cross-polarized radiation in broadside direction, which was not

considered in [12], is now completely eliminated because of geometrical symmetry.
In this paper, detailed synthesis and design of both the antenna is discussed. Type 1 Filtering Antenna is third order 2.45GHz Chebhyshev Bandpass Filtering Antenna in which the printed inverted-L antenna act as a last resonator and also as radiator. At first, synthesis is carried out and later the detailed design procedure is discussed. Type 2 filtering antenna is second order 5.2GHz Chebhyshev Bandpass Filtering Antenna. Synthesis and design procedure is discussed. Comparative analysis of both the designs is carried at the end. Both types of Filtering Antennas are unique in their own way, so considered here for study.

2. TYPE OF FILTERING ANTENNAS

As stated in introduction, there are numerous filtering antennas developed and designed, but filtering antennas considered in this paper for study are unique and provide better performance compared to others.

2.1 Type 1 Filtering Antenna

In this design, we have studied the synthesis and design of new printed Filtering antenna. Fig. 1[1] contains the Third order Chebyshev Bandpass Filter. The first two filter resonator are provided by the parallel half wavelength microstrip lines and the 3rd by inverted-L antenna. The inverted-L antenna is printed on 0.508mm thickness substrate of dielectric constant 3.38 and loss tangent 0.0027. The ground plane of the whole circuitry has a size of L×W=60×60mm. A 50Ω microstrip line of width 1.17mm is used to feed the antenna. For synthesis of Filtering Antenna, the printed inverted-L antenna used with it's equivalent circuit is extracted over the entire desired bandwidth. For simple fabrication and good circuit behaviour, a quarter-wave admittance inverter is used[1].

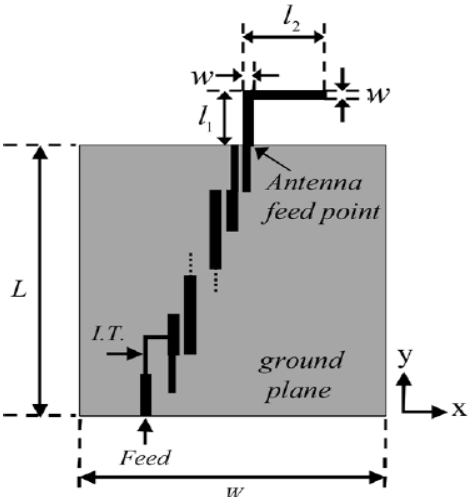

Fig -1: Geometrical Structure of Type 1 Filtering Antenna

2.1.1 Synthesis of inverted-L antenna

The inverted-L antenna is a monopole antenna and it exhibits series RLC resonance. The equivalent circuit components of the inverted-L antenna are obtained by optimization method using the IE3D electromagnetic simulator. This centre frequency is chosen to be 2.45GHz. Due to the presence of parasitic capacitance, the antenna frequency has to be slightly greater than the centre frequency. The antenna's reflection coefficient has it's minimum value at the location of antenna frequency, and is given by,

$$S_{11} = 20\ log\left|\frac{Y_{in} - Y_0}{Y_{in} + Y_0}\right|$$

The quality factor of the antenna can be used for synthesizing the filtering antenna, given by

$$Q_A = \frac{2\pi f_0 L_A}{R_A}$$

The effect of parasitic capacitance has not been considered in Q_A and hence, it's not the whole quality factor of the antenna. It can be seen that quality factor of antenna decreases as the radiation resistance increases. The dimensions of the inverted-L antenna are $l_1 = 10mm$, $l_2 = 17.25mm$, and $w = 1.17mm$. The extracted equivalent circuit components are $L_A = 14.2nH$, $C_A = 0.30pF$, $R_A = 28.6\Omega$ and $C_g = 0.37pF$ with antenna resonant frequency, $f_A = 2.53GHz$[1].

2.1.2 Synthesis of Filtering Antenna

We have to synthesize and design 3rd order Chebyshev Bandpass Filter in which, first two orders (filter resonators) are provided by the parallel coupled lines sections and the last order is contributed by the inverted-L antenna. The synthesis of 3rd coupled line section is different from the other two, as it has to match to the low radiation resistance of the inverted-L antenna. The actual response of a circuit can be obtained by the sum of the response of the circuit to even and odd mode excitations. In even mode, voltage potentials are same and it replicates the magnetic wall, whereas, in odd mode, voltage potentials are opposite and it replicates electric wall.
The image impedance and propagation constant of both the circuits are calculated and equated to obtain the even- and odd-mode characteristics impedances, given by

$$Z'_{0eN} = Z_a\left[{Z_0}/{Z_a} + J'_N Z_0 + (J'_N Z_0)^2\right]$$

$$Z'_{0eo} = Z_a\left[{Z_0}/{Z_a} - J'_N Z_0 + (J'_N Z_0)^2\right]$$

As we have obtained equivalent circuits of coupled line sections and inverted-L antenna, the filtering antenna structure can be expressed as [1],

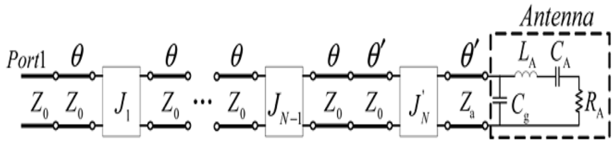

Fig -2: Structure of Type 1 Filtering Antenna

2.1.3 Design of Filtering Antenna

Step 1:-
At start, state the specifications of filter to be designed. With the help of these specifications, admittance inverters $J_n Z_0\ (n = 1, 2 \ldots N + 1)$ and the parallel resonators $L_n C_n (n = 1, 2 \ldots\ldots N)$ can be obtained.
Specifications of Bandpass Filter to be synthesized:-

- A third order Chebyshev Bandpass Filter (i. e N=3), with 0.1dB equal-ripple response.
- Centre Frequency is 2.45GHz
- Fractional Bandwidth is 0.14.

The values of parallel resonators for n=4 are given by,

- $L = \frac{2Z_0}{\pi f_0} = \frac{2\times 50}{\pi \times 2.45GHz} = 2.068nH$
  $C = \frac{1}{L f_0^2} = \frac{1}{2.068n \times 2.45G^2} = 2.041pF$
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Step 2:-
As antenna is used as a last resonator and load impedance of the bandpass filter, specify the antenna structure to be used. Here, the printed inverted-L antenna is used for this purpose.
Step 3:-
At this step, obtain all the dimensions of the inverted-L antenna. For this, calculate the antenna quality factor given by,

$$Q_A = \frac{\pi}{2(Z_0 J_4)^2} = \frac{\pi}{2(50 \times 0.4617)^2} = 7.37$$

Step 4:-
At this step, select the appropriate characteristic impedance, Following, the even- and odd- mode characteristics impedances of the third coupled line section can be obtained as,

$$Z'_{0e3} = Z_a\left[\frac{Z_0}{Z_a} + J'_3 Z_0 + J'_3 {Z_0}^2\right] = 75.67\Omega$$

$$Z'_{0o3} = Z_a\left[\frac{Z_0}{Z_a} - J'_3 Z_0 + J'_3 {Z_0}^2\right] = 42.579\Omega$$

Step 5:-
Now, obtain the even- and odd- mode characteristic impedances of 1st and 2nd coupled line sections as,
For 1st coupled lines section,

$$Z_{0e1} = Z_0\left[1 + J_1 Z_0 + J_1 {Z_0}^2\right] = 83.77\Omega$$

$$Z_{0o1} = Z_0\left[1 - J_1 Z_0 + J_1 {Z_0}^2\right] = 37.57\Omega$$

For 2nd coupled lines section, $Z_{0e2} = 60.125\Omega$ and $Z_{0o2} = 41.937\Omega$. In this way, the designing of Filtering Antenna is achieved.

2.2 Type 2 Filtering Antenna

The geometry of the second filtering microstrip antenna is depicted in Fig. 3[2]. The structure is printed on one side of a Rogers RO4003 substrate with dielectric constant 3.38 and thickness 0.508 mm. The antenna has an all-planar structure with geometrical symmetry to the yz plane. The filtering antenna consists of three parts- the U-shape radiating patch, the T-shape resonator, and the feeding microstrip line. The yellow part is the metallic patch[2].

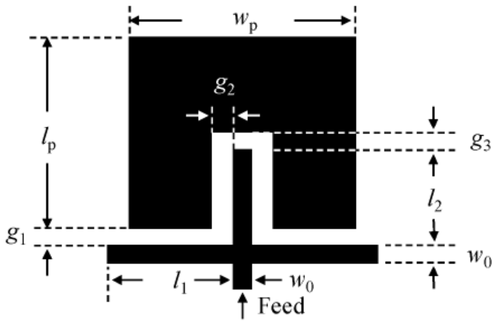

Fig -3: Geometrical Structure of Type 2 Filtering Antenna

Fig. 4 shows the corresponding equivalent circuit model of the filtering antenna[2]. In an antenna designer point of view, the T-shape resonator and the U-shape patch are modeled by the parallel $L_1 C_1$[6] and $R_L L_2 C_2$[14] circuits, respectively. In the filter designer point of view, at the bottom of Fig. 4, the T-shape resonator corresponds to the first-stage resonator $L_1 C_1$, and the U-shape patch corresponds to the second-stage resonator $L_2 C_2$ with the load. The coupling between these two resonators mainly comes from the quarter-wavelength parallel section, which is similar to the parallel coupled lines, and thus can be modeled by a J (admittance) inverter [13]. Since the equivalent circuit is exactly the same as the bandpass filter prototype, by employing the synthesis method of filters, the filtering microstrip antenna can be designed with the filter response.

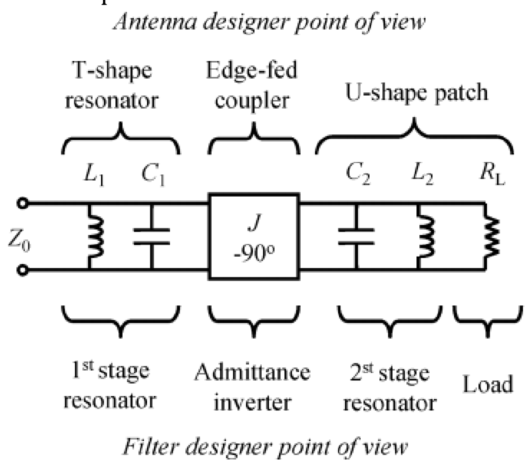

Fig -4: Equivalent Circuit of Type 2 Filtering Antenna

2.2.1 Second-Order Chebyshev Bandpass Filter Prototype

The bandpass filter prototype is chosen to be with a second-order Chebyshev equal-ripple response, with the ripple level $L_a = 0.3$, center frequency 5 GHz, and port impedance $Z_0 = 50\Omega$. For an ideal Chebyshev filter, the minimum return loss in passband is

$$RL(dB) = -10\log\left(1 - 10^{-\frac{L_a}{10}}\right)$$

In this case, $RL = 11.75dB$. The fractional bandwidth is set as 2%, which is about twice that of a well-matched ordinary inset-fed microstrip antenna. Once we get these filter parameters, the element values in Fig. 4 can be easily obtained[6]:

$$C_1 = C_2 = 37.4\ pF, L_1 = L_2 = 27.0\ pH,\ J = 26.0\ ms\ and\ R_L = Z_0 = 50\Omega$$

2.2.2 U-Shape Patch Design

The coupling mechanism affects the response of the resonator a lot. Thus, while extracting the parameters, the J-inverter is inseparable. There are $R_L L_2 C_2 -$three parameters to be determined. The patch width mainly affects the radiation resistance R_L , and the patch length dominates the resonant frequency, i.e., the product of L_2 and C_2. The ratios of L_2 and C_2 are determined by the substrate thickness.

2.2.3 T-Shape Resonator Design

The product and ratio of L_1 and C_1 determine the resonant frequency and external quality factor, respectively. The required external quality factor of the first stage can be calculated by [13]

$$Q_{e1} = Z_0\sqrt{\frac{C_1}{L_1}}$$

The $L_1 C_1$ resonator in Fig. 4 is realized by the T-shape resonator. $(l_1 + l_2)$ is almost half a wavelength at 5 GHz. When $l_1 = 10.91mm\ and\ l_2 = 7.43mm$, this results in $Q_{e1} = 59$ this satisfies the requirement.

3. RESULTS AND DISCUSSION

Simulation of the design is performed on the IE3D electromagnetic simulator. IE3D is an integral full-wave electromagnetic simulation and optimisation package for the analysis and design of 3D and planar microwave circuits. Basically, it solves the Maxwell's Equation in an integral form. Simulation of both the designs is performed in IE3D due to its unique cell meshing[15].

3.1 Results of Type 1 Filtering Antenna

The structure was simulated in IE3D electromagnetic simulator. The yellow color indicates the metallic patch. As it is filtering antenna, we observe that only one port is connected i.e. to feed the circuit. Printed inverted-L antenna is the last resonator and also the radiator, so no port can be connected at its radiating end. Fig.6[15] shows the geometry of type 1 filtering antena designed in IE3D.

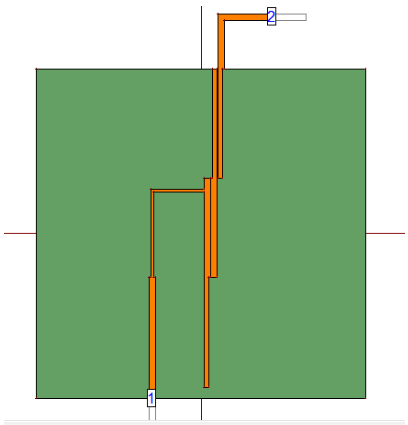

Fig -5: Geometry of Type 1 Filtering Antenna

The performance of microwave structures can be determined from the S-parameters of that structure. Here return loss of the structure is obtained by the simulator. The result obtained is favourable as the level of return loss is below -10 dB. This confirms the feasibility of the co-designed structure i.e. efficient integration of filter and antenna. When individually designed antenna is cascaded to the filter, it results in bad skirt selectivity. Fig. 6 shows the return loss obtained for type 1[15].

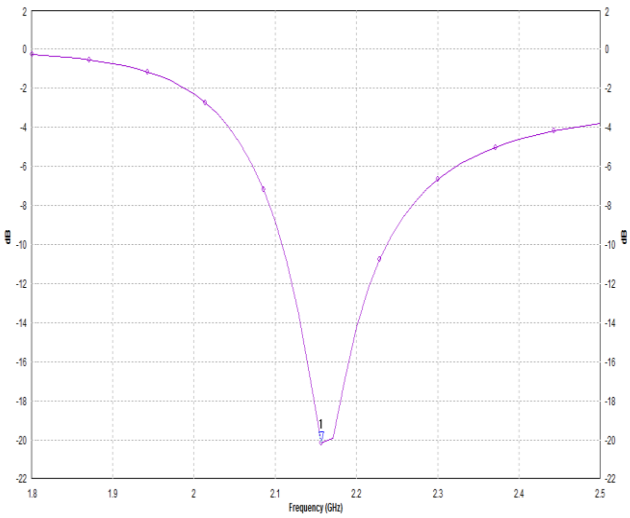

Fig -6: Simulation Results of Type 1 Filtering Antenna

3.2 Results of Type 2 Filtering Antenna

Simulation is performed in IE3D Electromagnetic Simulator. The symmetry of the geometry plays important role on the antenna gain. Symmetry eliminates the cross-polarized gain, so the symmetric filtering antenna has better selectivity and pure polarization. Fig.7[15] shows the geometry of type 2 filtering antena designed in IE3D.

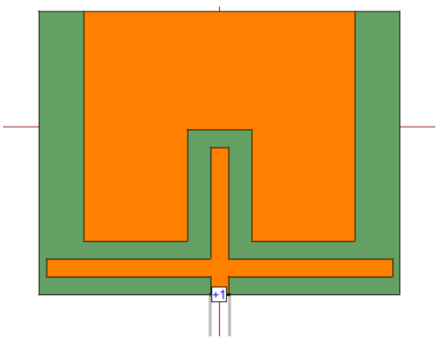

Fig -7: Geometry of Type 2 Filtering Antenna

Fig.8. shows the simulated return loss of the Type 2 filtering antenna[15]. Here, level of return loss is below -10dB, which confirms the feasibility of structure. This structure shows better results than the ordinary inset-fed microstrip antenna. Variation in the dieletric constant of the subtrates also leads to shift in the lower frequencies.

Referring to Fig.9[15], the strongest current distribution is concentrated on the two arms in x-direction, but flow in opposite directions. The copolarized radiation is contributed by the non-resonant microstrip in y-direction[2].

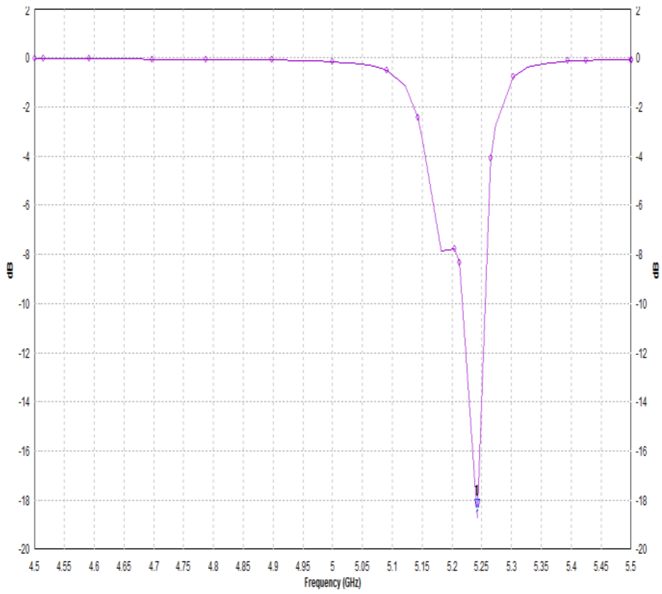

Fig -8: Simulation Results of Type 2 Filtering Antenna

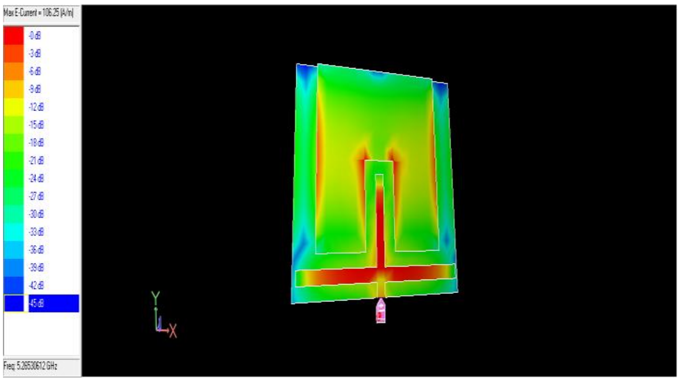

Fig -9: Current Distribution of Type 2 Filtering Antenna

4. CONCLUSION

The new printed Filtering Antenna is synthesized and designed by co-design approach. The equivalent circuit components of the inverted-L antenna were first extracted and then used for synthesis of Bandpass Filter. Firstly, the 3rd order Chebyshev Bandpass Filter was designed in which the last resonator and load impedance was provided by the inverted-L antenna. By integrating the filtering and radiating functions, we obtained a compact sized structure with less return loss. The design is approximately accomplished. Similarly, in second design, a second-order filtering microstrip antenna with quasi-elliptic function antenna gain response has been presented. The design process follows the synthesis method of a second-order Chebyshev bandpass filter. Because of the all-planar structure, it can be easily integrated in modern microwave circuit design, such as the pre-filtering of the printed antenna array.

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