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Design of a Wide-Band Microstrip Filtering Antenna with Modified Shaped Slots and SIR Structure

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Abstract: This paper presents a new compact microstrip filtering antenna with modified shaped slots to improve the impedance bandwidth. The proposed microstrip filtering antenna consists of three parts: the monopole radiating patch antenna; the Stepped Impedance Resonator (SIR) filter; and the feeding microstrip line. The designed structure is achieved on one-sided glass epoxy FR-4 substrate with dielectric constant ε_r = 4.4 and thickness h = 1.6 mm. The design procedure of the proposed filtering antenna starts from the second-order Chebyshev low pass filter (LPF) prototype. The achieved results show an excellent performance of S11-parameter with broadside antenna gain on +z-direction. Having two transmission zeros at 5.4 GHz and 7.7 GHz, good skirt selectivity and a wide-band impedance bandwidth of about 1.66 GHz makes the designed filtering antenna suitable for high-speed data communications. Both the simulation results generated by using the Computer Simulation Technology (CST) software package and the measurement achieved by using a vector network analyzer (HP 8510C) and the anechoic chamber show good agreement.

Keywords: microstrip filtering antenna; impedance bandwidth; FR-4; computer simulation technology; Chebyshev; LPF

1. Introduction

Increasing demand for compact transceiver applications continues to affect the field of microwave and radio frequency communications [1–4]. Some of the most important modules in such systems are the microstrip antennas and filters [5–40]. Microstrip Patch Antenna (MPA) has been designed and widely characterized a few years ago for several reasons, the most important was that it had a low profile, was lightweight and had a low fabrication cost [18]. Different techniques have been developed in order to achieve rapid solutions to enhance radiation specifications such as bandwidth and gain. The radiating patch can assume any possible geometry, including a rectangle, circle, square, dipole and triangle [19]. The microstrip monopole patch antenna is designed as a single-layer which usually consists of four parts: patch, a dielectric substrate, half ground plane and feedline [20]. Generally, the physical dimensions of a microstrip monopole patch antenna are small, but the electrical dimensions measured in wavelength λ are not small [21]. The designers of the microstrip antennas should also consider the electrical characteristics of these antennas such as center frequency f_0, voltage standing wave ratio (VSWR), return loss, gain and radiation pattern [22]. Rapid data transfer requires high channel capacities and needs more complex and bulky systems. Modern trends in electronic and communication systems proposed more compact and portable systems, therefore the designers of such systems faced a major challenge in realizing these complex systems and at the same time making them compact and portable enough to meet commercial market needs [23]. One way to minimize the overall circuit size and increase the bandwidth is to integrate the Stepped Impedance Resonator (SIR) filter with the monopole patch antenna in one single module [24]. This integration changes the structure of the circuit, improves the performance of the circuit and simplifies the connection among various components.

Unlike many microstrip filtering antenna proposed in the literature [35–44], the design proposed here is better than others with respect to the structure size, design complexity, gain, bandwidth and the reflection coefficient characteristics. Also, this paper presents a compact second-order filtering antenna utilizing SIR and modified shaped slots on the monopole patch antenna. By using SIR bandpass filter and adopting the modified shaped slots on the monopole patch antenna, the performance of the circuit has been improved, especially the bandwidth performance.

2. Design of the Filtering Antenna

The 3-D view of the proposed microstrip filtering antenna is described in Figure 1. The designed structure is printed on one side of a glass epoxy FR-4 substrate with dielectric constant ε_r = 4.4 and thickness h = 1.6 mm. The microstrip filtering antenna consists of three parts: the monopole radiating patch antenna, the SIR filter and the feeding microstrip line. The monopole patch antenna has dimensions of $w_p \times l_p$, with l_p about 0.863 λ_g at the operating frequency.

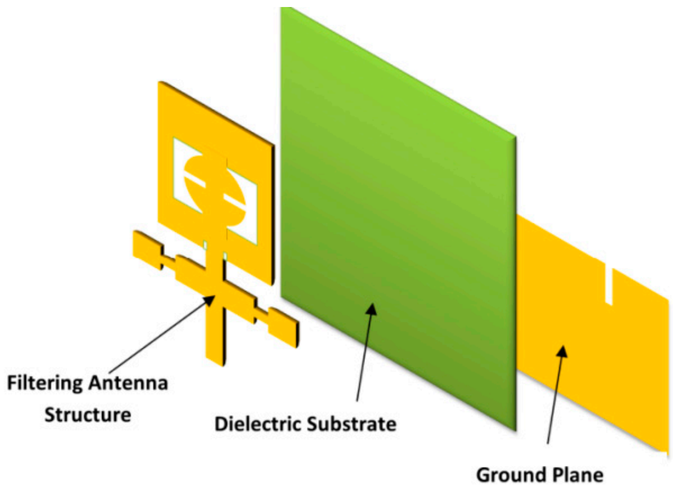

Figure 1. 3-D view structure of the proposed filtering antenna.

Notably, the equivalent circuit of the proposed filtering antenna is the same as the bandpass filter prototype. By utilizing the filter synthesis technique, the filtering antenna can be designed along with the filter response. The design procedure of the proposed filtering antenna starts from the second-order Chebyshev low pass filter prototype. The design parameters such as the center frequency, the fractional bandwidth (FBW), return loss and insertion loss are calculated and discussed. The lumped element values of the microwave circuit model shown in Figure 2a are available in the literature [23]. The following step is to design the resonator via the SIR structure and with a modified slot-shaped monopole patch antenna. Finally, the filter and antennas are integrated with fine-tuning to improve the performance. The simulation results throughout this research paper are accomplished by using Computer Simulation Technology (CST) software [25] and the measurement results are achieved using the vector network analyzer (HP 8510C) and an anechoic chamber. The designed structure with its optimized dimensions and photograph of the fabricated prototype for the proposed filtering antenna are presented in Figure 2 and Table 1.

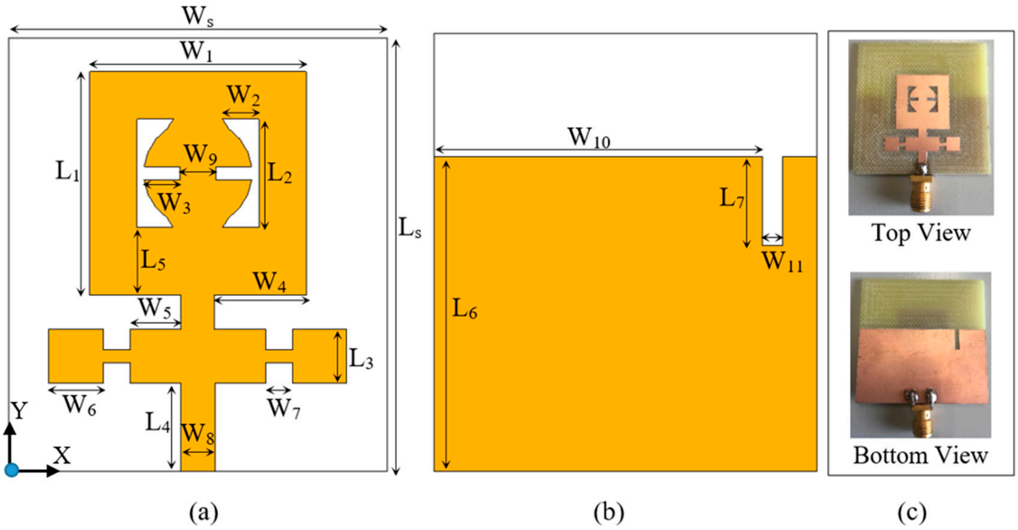

Figure 2. Geometry of the proposed filtering antenna with its optimized dimensions: (**a**) Top view (**b**) Bottom view (**c**) Photograph of the hardware realization.

Table 1. The optimized dimensions of the proposed filtering antenna (in mm).

Parameter	**W_1**	**W_2**	**W_3**	**W_4**	**W_5**	**W_6**	**W_7**	**W_8**	**W_9**	**W_{10}**
Dimensions	16	2.6	2.6	6.8	3.7	4	2	2.5	24	1.5
Parameter	**W_{11}**	**L_1**	**L_2**	**L_3**	**L_4**	**L_5**	**L_6**	**L_7**	**W_s**	**L_s**
Dimensions	1.5	16.5	8	4	6.5	5	23	6.5	28	30

The proposed filtering antenna shown in Figure 2 can be expressed by its equivalent circuits, as seen in Figure 3a. The equivalent circuit of the proposed filtering antenna is transferred to the conventional second-order bandpass filter equivalent circuits and can be implemented as shown in Figure 3b [26]. The SIR and monopole patch antenna are modeled by parallel L_1 C_1 [27] and L_A C_A R_A [28] lumped elements, respectively. According to the filter synthesis approach theory [29], the SIR is considered as a first stage resonator and the monopole patch antenna as the second stage resonator with an appropriate load impedance of R_A.

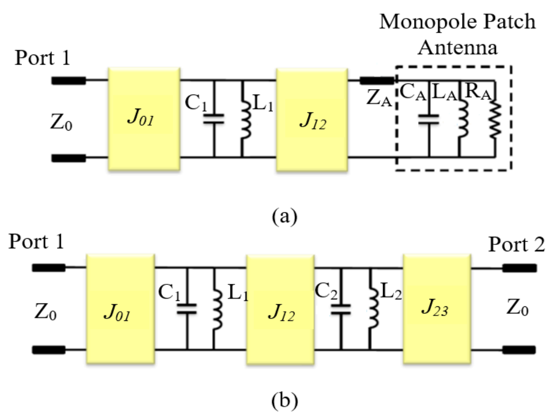

Figure 3. Microwave equivalent circuit: (**a**). The proposed filtering antenna (**b**). The second-order bandpass filter.

The resistance R_A in the equivalent circuit of the monopole patch antenna is considered as the load impedance of the bandpass filter to be synthesized, and the parallel L_A/C_A is the last circuit resonator of the filtering antenna. Then:

$$f_o = \frac{1}{2\pi\sqrt{L_A C_A}}. \quad (1)$$

The second-order bandpass filter is chosen as a Chebyshev equal-ripple response, with the ripple level L_A (dB) = 0.5, f_o = 6.45 GHz, and port characteristic impedance of Z_o = 50 Ω. The minimum return loss R_L (dB) in passband for an ideal Chebyshev bandpass filter is given as [30]:

$$R_L(dB) = -10\log\left(1 - 10^{-L_A(dB)/10}\right) \quad (2)$$

where, R_L = −18.2 dB, and the FBW = 25.7%.

The quality factor is one of the most critical parameters of the resonant circuit, and increasing its value means that lower loss in the resonant circuit will be achieved. The quality factor of the monopole patch antenna can be derived from the equivalent circuit of the proposed filtering antenna shown in Figure 3(a), and it is used for synthesizing the filtering antenna [31]:

$$Q_A = \frac{2\pi f_o L_A}{R_A}. \quad (3)$$

The values of LC components of the resonators are given by:

$$L = \frac{2Z_o}{\pi f_o} \quad (4)$$

$$C = \frac{1}{L f_o^2}. \quad (5)$$

After solving the above equations, L and C are found to be 4.93 nH and 4.87 Pf, respectively.

According to the above, for the second-order (N = 2) Chebyshev low pass filter prototype with a passband ripple of 0.5 dB, the element values are $g_o = 1$, $g_1 = 1.4029$, $g_2 = 0.7071$ and $g_3 = 1.9841$. Generally, for the equivalent circuit of the bandpass filter shown in Figure 3b, the theoretical values of the J-inverters can be readily obtained [32] as follows:

$$J_{01} = \frac{1}{Z_o}\sqrt{\frac{\pi FBW}{4 g_o g_1}} \quad (6)$$

$$J_{n-1,n} = \frac{1}{Z_o}\frac{\pi FBW}{4\sqrt{g_{n-1} g_n}}. \quad (7)$$

The second-order Chebyshev bandpass filter parameter values are summarized in Table 2.

Table 2. Second-order Chebyshev bandpass filter parameters.

Parameter	Value
FBW	0.257
g_o	1
g_1	1.4029
g_2	0.7071
g_3	1.9841
J_{01}	7.48×10^{-3}
J_{12}	4.688×10^{-3}
J_{23}	3.942×10^{-3}

3. Simulation and Measurement Results and Discussion

Defected ground structure (DGS) was commonly used in the microstrip filters and antennas to improve the S-parameters performance and achieve compact size structure [33]. The realization of the DGS is performed by inserting a defected shape on the ground plane to disturb the current shield distribution. Establish the shape and dimensions of the DGS, following which the disturbance at the ground shield current distribution controls the current flow and the input impedance of the proposed filtering antenna [34]. The excitation of the electromagnetic waves that propagate inside the dielectric substrate layer can also be controlled by the DGS. The S11-parameter of the proposed filtering antenna with and without DGS is shown in Figure 4. Recently, the DGS was used to enhance the stop-band rejection characteristics as illustrated in Figure 4. Figure 5 shows the S11-parameter of the proposed filtering antenna for different shaped slots loaded.

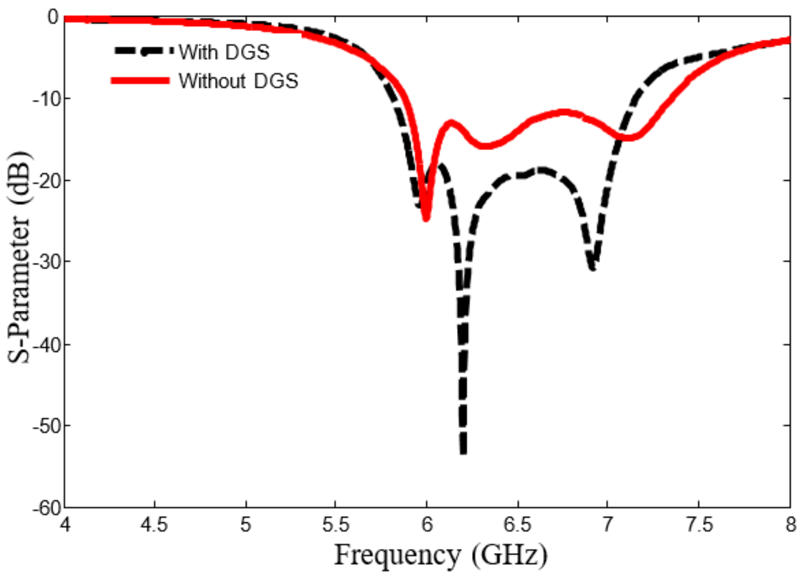

Figure 4. S11-parameter of the proposed filtering antenna with and without defected ground structure (DGS).

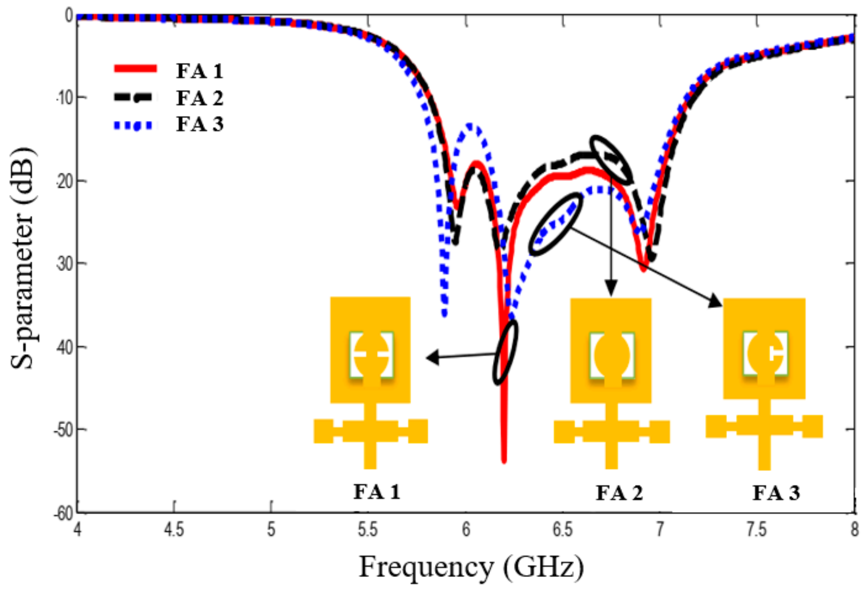

Figure 5. S11-parameter of the proposed filtering antenna (FA) for different shaped slots.

The performance of the proposed filtering antenna, in terms of return losses, radiation patterns and gains, have been studied and measured. The simulated and measured S11-parameter and gain of the proposed filtering antenna are shown in Figure 6. Based on these results, it is found that at the center frequency f_o = 6.45 GHz, the filtering antenna has two transmission zeros at 5.4 GHz and 7.7 GHz, with impedance bandwidth (BW) of about 1.66 GHz. Broadband is one of the most important requirements for modern digital communication, which requires transmitting and receiving a huge bit rate. Therefore, this design is suitable for high-speed data communication.

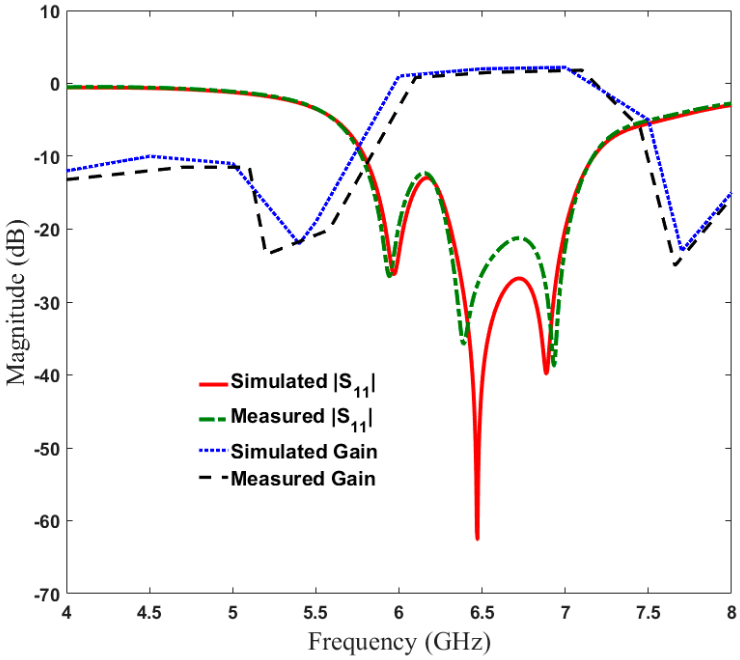

Figure 6. S11-parameter and gain of the proposed filtering antenna.

Figure 7 shows the measured and simulated radiation patterns of the proposed filtering antenna at the resonant frequency. Full-wave simulation is carried out using CST software and the measurement radiation pattern is observed inside the anechoic chamber. Eϕ represents the co-polarization properties, while Eθ represents the cross-polarization properties. The yz-coordinates are taken into account as the E-plane, and the xz-coordinates as the H-plane.

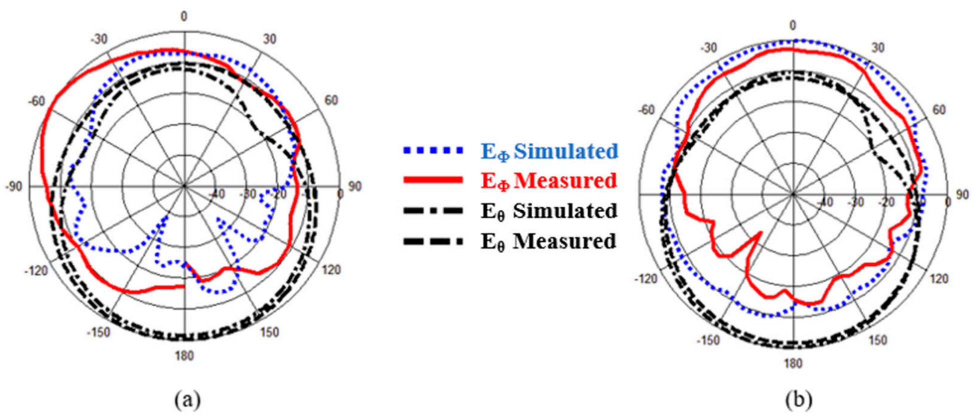

Figure 7. Simulated and measured radiation patterns for the proposed filtering antenna (**a**) xz plane, and (**b**) yz plane.

The simulated and measured radiation pattern characteristics of the filtering antenna are roughly invariant, with a good performance of the S11-parameter and broadside antenna gain on +z-direction. The peak gain of the achieved pattern is about 3 dB, which provides good skirt selectivity. Both the simulation results generated by using the CST software package and the measurement achieved from the vector network analyzer (HP 8510C) and anechoic chamber show fairly good agreement. Variations between the simulated and measured results may arise due to the connection of the antenna to the non-ideal absorber by coaxial cable in the anechoic chamber. Table 3 compares this proposed microstrip filtering antenna with other designs that have similar configurations and performances. The design proposed here is better than others with respect to the structure size, design complexity, gain, bandwidth and the reflection coefficient characteristics.

Table 3. Comparison between the proposed design and others.

Ref.	CF (GHz)	3 dB Fractional Bandwidth (%)	Size ($\lambda_g \times \lambda_g$)	RL (dB)	Gain (dB)	Extra Structure
[35]	2.5	15	11×11	>15	2	Multi-layer
[36]	5	2	1.3×1.13	>15	4	None
[37]	2.45	6.4	9.7×9.5	>15	6	None
[38]	2.5	16.3	0.8×0.5	>20	2.4	None
[39]	2.5	8	6×6	>14	4.5	None
Prop.	6.5	30	1.2×1	>30	3	None

4. Conclusions

A new and compact filtering antenna with modified shaped slots has been designed, fabricated and measured in a microstrip transmission line. The proposed filtering antenna was analyzed by utilizing the filter synthesis approach and based on the equivalent circuit and specifications of the second-order Chebyshev low pass filter. The proposed filtering antenna structure with the SIR technique provides good skirt selectivity. The design shows good performance and is suitable for high-speed communication applications. Both the simulation results generated by using the CST software package and the measurement achieved by the vector network analyzer and anechoic chamber show good agreement.

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