New Printed Filtering Antenna with Selectivity Enhancement

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摘要— 本計劃提出新型印刷式濾波天線之設計，具有選擇性改善之功能，其利用共同設計(co-design)之方法，將印刷式曲折式天線(meander-line antenna)及四分之一波長共振器(quarter-wavelength resonator)整合而成濾波天線。在此，倒 L 型天線不僅可作為一個輻射體，還可作為濾波器最後一階的共振器。於本研究中亦提出新型的四分之一波長共振器，其可提供高電容值的並聯共振電路及產生二個額外的傳輸零點(transmission zero)，以改善邊緣選擇性。詳細的設計步驟在本文亦被提出，可透過濾波器之規格來實現之。以操作頻率為 2.45GHz 且具 0.1 dB 等漣波響應之二階柴比雪夫濾波器為例子來設計一濾波天線，所提出之架構有較好的設計準確性與濾波器邊緣選擇性。所量測之結果與設計的做比較，包括折反損耗(return loss)、輻射增益對頻率(radiation gain versus frequency)之響應，具有良好的一致性。

關鍵字—柴比雪夫帶通濾波器，濾波天線，曲折式天線，四分之一波長共振器，邊緣選擇性，傳輸零點。

***Abstract*— In this paper, a new printed filtering antenna with selectivity enhancement is presented. Based on the co-design approach, the printed meander-line antenna and a quarter-wavelength resonator are used and integrated to be the filtering antenna. Here, an antenna performs not only a radiator but also the last resonator of the bandpass filter. A new structure of the quarter-wavelength resonator is also proposed, which can provide a shunt resonator with high capacitance and introduce two extra transmission zeros for selectivity enhancement. According to the filter specifications, a design procedure is depicted in detail. One example of a 2.45 GHz two-pole filtering antenna is described based on the second-order Chebyshev bandpass filter with 0.1 dB equal-ripple response. Furthermore, the proposed structure supply good filter skirt selectivity. The measured results, including the return loss and antenna gain versus frequency, have good agreement with the designed one.**

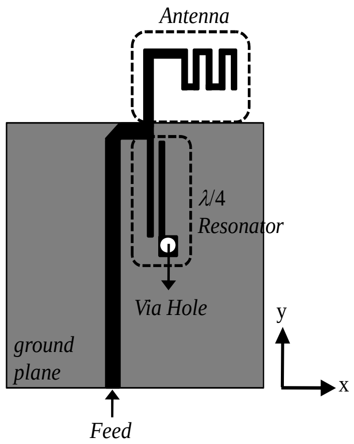

Fig. 1 Configuration of the proposed filtering antenna.

***Index Terms*—Chebyshev bandpass filter, filtering antenna, meander-line antenna, quarter-wavelength resonator, skirt selectivity, transmission zero.**

I. Introduction

With rapid development of wireless communication systems, the requirements for compact, low-cost, and low profile passive components are demanded in recent years. To achieve these purposes, various efforts could be designed simultaneously in a single circuit module. Therefore, an example for the integration of the filter and antenna, which is called the filtering antenna, is an important issue that should be solved. To date, however, there has thus far been relatively little study to establish the simple structure and good circuit behaviour.

There have been numerous studies in the literature for integrating the filter and antenna into a single microwave device [1]-[4]. For the purpose of reducing circuit area, a pre-designed bandpass filter with suitable configuration was directly inserted into the feed position of a patch antenna [1]. For the required bandwidth, the bandpass filter can be integrated properly with the antenna [2]-[4] by using an extra impedance transformation structure in between the filter and the antenna. Nevertheless, the transition structure needs extra circuit area, and the designs did not have good filter responses between the frequency ranges.

In more recent years, the filtering antennas designed following the synthesis process of the bandpass filter have been presented in [5]-[8]. In these designs, the last resonator and the load impedance of the bandpass filter were substituted by an antenna that exhibited a series or parallel RLC equivalent circuit. Although they have been done based on the co-design approach, these filtering antennas did not show good filter performance, especially the band-edge selectivity and out-band rejection. This is due to the lack of the extraction of the antenna's equivalent circuit over a suitable bandwidth. Only that at the center frequency was extracted and used in the filter synthesis. Moreover, the antenna gain versus frequency, which is an important characteristic of the filtering antenna, was not examined in these studies.

In this paper, a new co-design approach with efficient integration is proposed to realize a printed filtering antenna. The printed meander-line antenna is utilized and the proposed quarter-wavelength ($\lambda/4$) resonator is also presented to produce the proposed filtering antenna.

II. Equivalent Circuit of the Quarter-Wavelength Resonator and Meander-Line Antenna

Fig. 1 shows the proposed two-pole filtering antenna, which contains a $\lambda/4$ resonator with new structure and a meander-line antenna. Here, the $\lambda/4$ resonator and antenna are to be designed as the first and last resonators in filtering antenna, respectively. In order to integrate the proposed filtering antenna with the efficient integration, the equivalent circuit model of the $\lambda/4$ resonator and antenna should be analysed and discussed in detail.

A. *λ/4 Resonator*

To realize the shunt resonator, the short-stub $\lambda/4$ microstrip line can be employed. However, when the shunt resonator with high capacitance is selected, the large circuit area for the resonator should be required; it is not a convenient way to design the filtering antenna. Therefore, in this work, a new structure of $\lambda/4$ resonator is proposed, which can resolve this issue. Fig. 2(a) illustrates the geometry of the proposed $\lambda/4$ resonator, which composes of an open-stub $\lambda/4$ microstrip resonator and a short-end $\lambda/4$ microstrip resonator. It is noted that the short-end $\lambda/4$ microstrip resonator is coupled by the open-stub $\lambda/4$ microstrip resonator. The equivalent circuit of the proposed $\lambda/4$ resonator is shown in Fig. 2(b) and its further equivalent circuit with the composite shunt resonator can be shown in Figs. 2(c). For the composite shunt resonator, the two series resonators have reactance X_a and X_b, and resonate at f_a and f_b, respectively. Suppose $f_a < f < f_b$, it can be observed that $X_a > 0$ is inductive and X_b is capacitive. Hence, the left and right series resonator in Fig. 2(c) will produce the low-frequency transmission zero (f_a) and high-frequency (f_b) transmission zero, respectively. Furthermore, the composite shunt resonator in Fig. 2(c) can be represented by a shunt resonator shown in Fig. 2(d), which resonates at f_r [9].

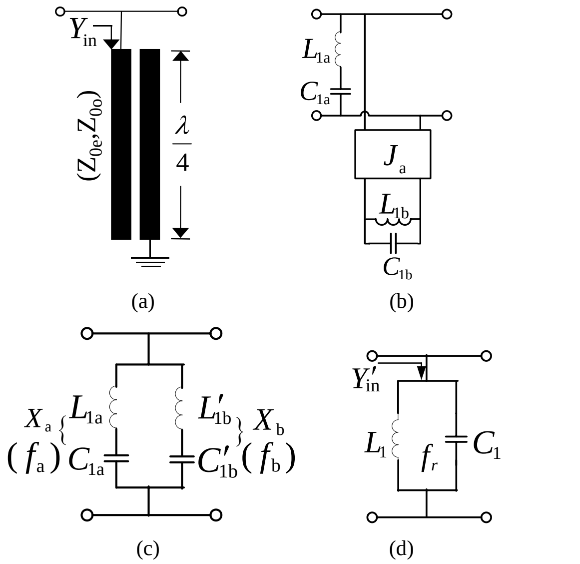

Fig. 2 (a) Geometry of the λ/4 resonator. (b) Equivalent circuit of the λ/4 resonator. (c) The composite shunt resonator with two series LC resonators in parallel. (d) The equivalent shunt LC resonator around the resonant frequency ω_r.

The proposed λ/4 resonator shown in Fig. 2(a) can be defined as a coupled line section, which only has one feed port. Consequently, based on the analysis of parallel coupled line circuit [10], the input admittance Y_{in} in Fig. 2(a) is derived as

$$Y_{in} = j\frac{\pi(Z_{0e}+Z_{0o})}{f_r(Z_{0e}-Z_{0o})^2}\Delta f \qquad (1)$$

with

$$f_r = \frac{1}{2\pi\sqrt{L_1C_1}}$$

where Z_{0e} and Z_{0o} are the even- and odd-mode characteristic impedances of the proposed λ/4 resonator, respectively. Moreover, the input admittance Y'_{in} in Fig. 2(d) can be obtained as

$$Y'_{in} = j4\pi C_1\Delta f \qquad (2)$$

By letting the admittance Y_{in} and Y'_{in} equal, where

$$\frac{(Z_{0e}+Z_{0o})}{(Z_{0e}-Z_{0o})^2} = \frac{2}{\pi}\sqrt{\frac{C_1}{L_1}} \qquad (3)$$

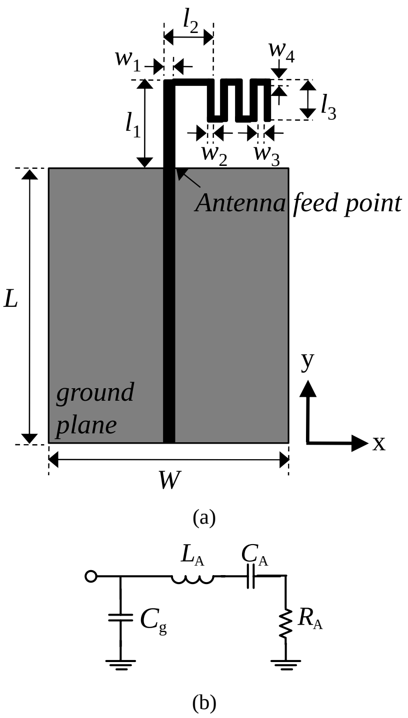

Fig. 3 (a) Geometry of the meander-line antenna and (b) the corresponding equivalent circuit model.

According to (3), when f_r and C_1 are chosen, the value of (Z_{0e}, Z_{0o}) can be selected arbitrarily and then the dimensions of the proposed λ/4 can be received.

B. *Meander-line Antenna*

In this research, an antenna which exhibits a series RLC resonance with high inductance is used to substitute the last resonator and load impedance of the filter. Since the meander-line antenna is a variety of a monopole antenna, the antenna exhibits a series RLC resonance near the first resonant frequency [11], which is suitable to design the filtering antenna. Fig. 3 (a) shows the geometry of the meander-line antenna and Fig. 3 (b) depicts the equivalent circuit at the antenna feed point looking toward the antenna. Here, L_A and C_A express the resonant inductance and capacitance of the antenna, respectively, and R_A corresponds to the antenna radiation resistance. It is noted that an extra shunt capacitance C_g is incorporated in the equivalent circuit here so that, as will be seen below, the whole circuit will have the same impedance behavior as the antenna itself in a wider frequency range. This parasitic capacitance comes from the accumulation of charges around the antenna feed point due to the discontinuity of the ground plane.

The antenna resistance R_A in the equivalent circuit will serve as the load impedance of the bandpass filter to be synthesized, and the series L_A-C_A circuit will be the filter's last resonator so that

$$f_0 = \frac{1}{2\pi\sqrt{L_A C_A}} \quad (4)$$

where f_0 is the center frequency of the bandpass filter. Note that owing to the existence of the parasitic capacitance, the resonant frequency f_A of the antenna is higher than f_0. This means that, in order to attain (4), the antenna should be designed at a frequency higher than the bandpass filter frequency.

III. Synthesis of the Filtering Antenna and Design Example with Experimental Verification

Fig. 4(a) shows the equivalent circuit model of the proposed filtering antenna (Fig. 1). Besides, the equivalent circuit of Fig. 4(a) can be transferred to the conventional second-order bandpass filter circuit, as shown in Fig. 4(b). Here, $L_A = L_2$, $C_A = C_2$, $R_A = R_o$, and $C_1' = C_1 + C_g$. The design procedures of the proposed filtering antenna can be summarized as follows.

1) Specify the requirements of the bandpass filter to be synthesized, including the operating frequency f_0, the fractional bandwidth Δ, and the type of the filter (e.g., bandpass filter with equal ripple). Therefore, the element values of the typical bandpass filter can be calculated [10].
2) Choose the suitable dimensions of the meander-line antenna and then extract the element values of its equivalent circuit. Here, these element values of antenna can substitute for the last resonator and load impedance of the bandpass filter and satisfy the requirements in design procedure (1).

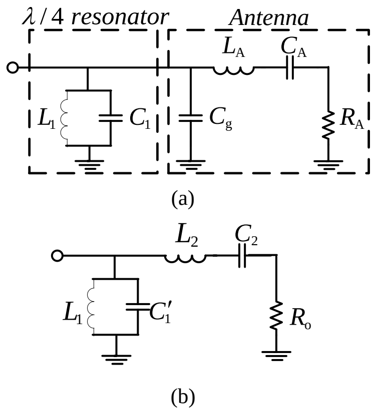

Fig. 4 (a) Equivalent circuit of the proposed filtering antenna. (b) Equivalent circuit of the typical two-pole bandpass filter.

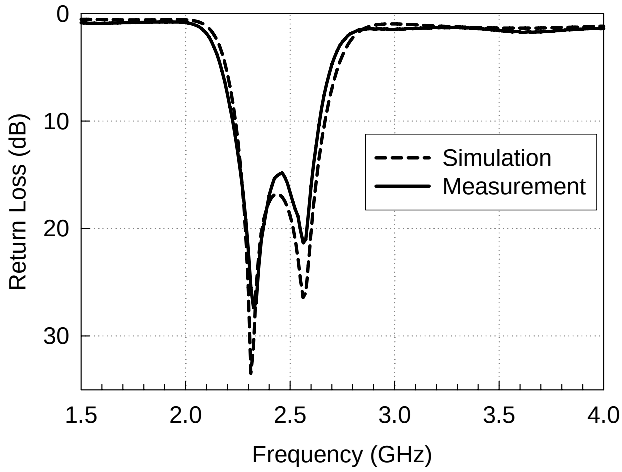

Fig. 5 Measured and simulated return losses of the proposed filtering antenna.

3) Calculate $C_1 (= C_1' - C_g)$ and select suitable values of (Z_{0e}, Z_{0o}) by using (3), and then the dimensions of the λ/4 resonator can be obtained.
4) Connect the two circuits directly.

Furthermore, an example of the proposed filtering antenna is to be presented. The filtering antenna is to be fabricated on a 0.508mm Rogers 4003 substrate with a dielectric constant of 3.38 and loss tangent of 0.0027. The ground plane size $L \times W$ = 60 mm × 60 mm. In this design, the full-wave simulation solver HFSS [12] is used. Following the above design procedures, a second-order Chebyshev bandpass filter with a 0.1 dB equal- ripple response is firstly chosen. The bandpass filter has a operating frequency f_0 = 2.45

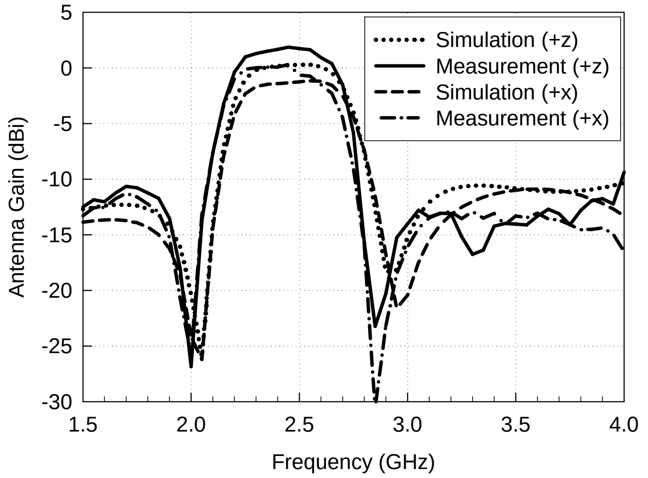

Fig. 6 Measured and simulated antenna gain versus frequency of the proposed filtering antenna.

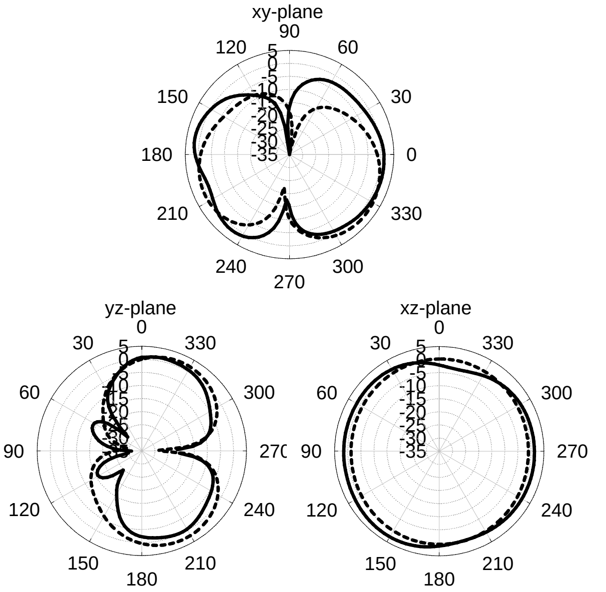

Fig. 7 Measured and simulated total-field radiation patterns in the xy, yz, and xz planes for the proposed filtering antenna. [solid line: measured results; short dash line: simulated results]. f_0 = 2.45 GHz.

GHz, a fractional bandwidth Δ = 14%, and Z_0 = 50 Ω. Owing to these requirements, the values of the circuit components for the filter (shown in Fig. 4(b)) can be obtained as L_1 = 0.539 nH, $C_1' = 7.823$ pF, L_2 = 14.431 nH, C_2 = 0.292 pF, and R_o = 36.9 Ω. Therefore, the dimensions of the meander-line antenna to be selected, which are l_1 = 15 mm, l_2 = 3.8 mm, l_3 = 5 mm, w_1 = 1.17 mm, w_2 = w_4 = 0.5 mm, and w_3 = 0.3 mm, and then the most approximate values of equivalent component for the antenna can be extracted as L_A = 14.42 nH, C_A = 0.293 pF, R_A = 36.7 Ω, and C_g = 0.266 pF. To calculate C_1 = 7.557 pF in third design procedure, the value of Z_{0o} for the λ/4 resonator is 62.2 Ω by using (3) (let Z_{oe} = 110 Ω), and then the dimensions of λ/4 resonator can be obtained. It should be noted that the resonant frequency of λ/4 resonator is f_r (about 2.494 GHz) due to the effect of the parasitic capacitance of antenna, C_g. Here, when Z_{0e} of the λ/4 resonator is decreasing, the gap size of λ/4 resonator will become narrower. Finally, the λ/4 resonator and meander-line antenna are to be connected directly, as shown in Fig. 1.

The simulated and measured return losses of the proposed filtering antenna are shown in Fig. 5. It is observed that the proposed filtering antenna provides good skirt selectivity. The simulated and measured antenna gain versus frequency in the +z direction and +x direction for the proposed filtering antenna are depicted in Fig. 6. It is obvious that the responses of the antenna gain versus frequency also have sharp skirt selectivity. Here, the measured antenna gains at operating frequency in the +z direction and +x direction are 1.865 dBi and 0.314 dBi, respectively. Meanwhile, it can found that these responses shown in Fig. 6 have two transmission zeros near f = 2 GHz and 2.9 GHz, which are produced by the proposed λ/4 resonator. The measured and simulated total-field radiation patterns at f_0 = 2.45 GHz in the three principal planes are also presented in Fig. 7. It is seen that the measured patterns have good agreement with the simulated ones. The radiation pattern in the *xz*-plane is nearly omnidirectional with peak gain of 2.78 dBi.

IV. CONCLUSIONS

A filtering antenna with new structure, which is realized by the co-design method, has been discussed in this paper. The design is accomplished by first establishing and analyzing the circuit models of the proposed λ/4 resonator and antenna, which can be employed as the first and last resonators of filter, respectively. Meanwhile, the antenna is also a radiator for the proposed structure. Based on the same equivalent circuit and specifications of the conventional second-order Chebyshev bandpass filter, the proposed filtering antenna has been designed by using the design procedures. The proposed structure provides good skirt selectivity as the conventional bandpass filter.

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A Compact Edge-Fed Filtering Microstrip Antenna with 0.2 dB Equal-Ripple Response

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摘要— 本計劃提出利用濾波器之合成方法，設計二階 0.2 dB 等漣波響應、頻寬為 4%之小型化濾波微帶貼片天線(microstrip patch antenna)。此輻射貼片利用新型邊緣饋入、缺口藕合(edge-fed gap-coupling)的方式進行天線饋入。而藕合的部份除了可激發天線，亦可做為濾波器設計中的電導轉換器(admittance inverter)。此外，所提出架構並不佔據額外的電路面積，其電路大小僅 $0.6\lambda_g \times 0.6\lambda_g$ ，其中λ_g為基板中導波波長。所提出之天線提供良好的選擇性、平坦的帶通天線增益響應、良好的外頻帶抑制。所量測之結果與設計的做比較，具有良好的一致性。

關鍵字—濾波微帶貼片天線，電導轉換器，缺口藕合，天線增益。

***Abstract*— A compact microstrip antenna with a second order 0.2 dB equal-ripple response and 4 % fractional bandwidth is proposed. This design follows the synthesis process of the bandpass filter. The radiating patch is fed by a new edge-fed gap-coupling mechanism. The coupling section excites the antenna, and it can be an admittance inverter for the filter design as well. Moreover, it does not occupy any additional circuit area. The proposed antenna has the size of $0.6\lambda_g \times 0.6\lambda_g$, where λ_g is the guiding wavelength in the substrate. The antenna provides good selectivity, flat in-band antenna gain response, and good out-band rejection. The measurement results agree with the simulated ones.**

***Index Terms*—microstrip patch antenna, admittance inverter, gap-coupling, antenna gain.**

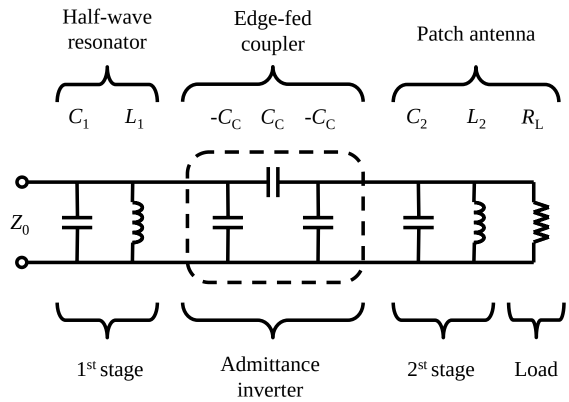

Fig. 1. Equivalent circuit of the proposed antenna.

I. Introduction

In an RF front-end system, a bandpass filter is usually cascaded to the antenna to reject spurious signal that received or transmitted by the antenna. For reducing the circuit size and increasing the system performance, one of the options is to integrate the bandpass filter and the antenna in a single module which has both the filtering and the radiating function.

In most of the antenna designs, the antenna itself is a resonator which resonates at the operation frequency. The radiation loss can be modelled by the radiation resistance of the antenna. Hence, the antenna has an equivalent RLC resonator response and can be treated as the last stage of the filter with a resistive load in filter design.

Several researches on antenna design follow the synthesis process of the bandpass filter [1-4]. However, these structures are complicated, and the in-band response, the band-edge skirt steepness, and the out-band suppression generally do not have performances. In [4], a patch antenna and one stage filter are integrated in a module. This structure needs an extra microstrip section as an admittance inverter. In order to save the circuit size, we replace the extra admittance inverter by the edge-fed gap-coupling scheme.

The edge-fed gap-coupling methodology was proposed by Kumar *et. al*. [5-6]. Several radiating patches are placed beside the feeding patch for broadband characteristics. Yet, the size of the gap-feed patch antenna is too large for practical usage. Some recent researches on the gap coupling feed scheme are summarized in [7]. Still, the required circuit areas are huge.

In this paper, we develop an antenna with the filtering function by the synthesis process of bandpass filters [8]. Additionally, a new edge-fed gap-coupling methodology for exciting the antenna was presented. The coupling section not only feeds the antenna, but also acts as the admittance inverter in the filter synthesis procedure. Most important of all, it does not need an additional space.

II. Antenna Configuration

The antenna design starts from the bandpass filter prototype [8]. The first step is to design an equal-ripple response lumped element filter at 12 GHz with 0.2 dB ripples and 4 % fractional bandwidth. The circuit model is shown in Fig. 1. Two parallel LC-resonators resonate at 12 GHz with the element values C_1 = C_2 = 5.9 pF and L_1 = L_2 = 0.03 nH. These two resonators are connected by an admittance inverter which is implemented by the standard Π-section capacitors with C_C = 0.308 pF. The load impedance and the port impedance are set to be R_L = 50 Ω and Z_0 = 50 Ω, respectively.

And then we observe this circuit in another point of view, as shown at the top of Fig. 1. We implement the first stage of the filter by a half-wavelength resonator. The half-wavelength resonator is design to have the same response as the LC-resonator. The parallel RLC-resonator (C_2, L_2, and R_L) is realized by an antenna. The antenna is fed by the electromagnetic coupling between the resonator and the antenna.

The detail parameters of the proposed antenna are shown in Fig. 2. The structure is printed on an RO4003 substrate with 20 mil thickness and dielectric constant 3.38. The structure consists of three parts – the L-shape half-wavelength resonator,

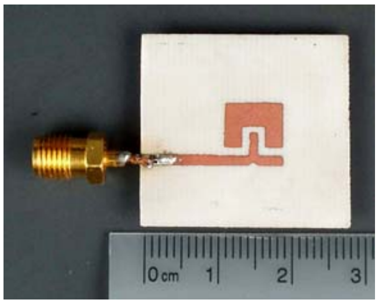

Fig. 3. Photograph of the fabricated circuit.

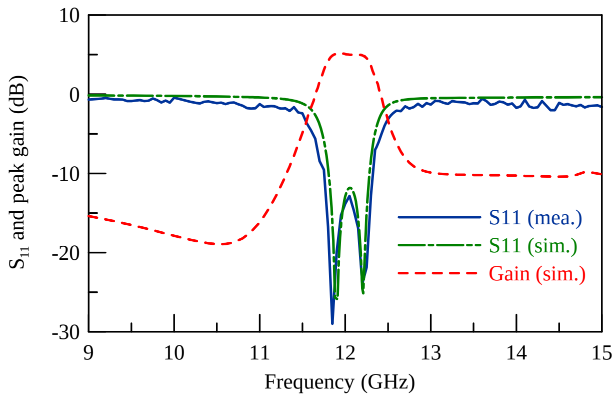

Fig. 4. The measured and simulated S_{11} and gain in +*z*-

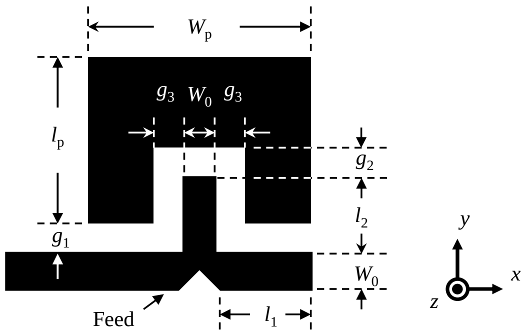

Fig. 2. Dimension of the antenna. W_p = 7.9 mm, l_p = 5.97 mm, W_0 = 1.17mm, l_1 = 3.415 mm, l_2 = 3.05 mm, g_1 = 1.1 mm, g_2 = 0.9 mm, and g_3 = 0.965 mm.

the feeding microstrip line, and the inverted U-shape radiating patch,

The L-shape resonator is a bended half-wavelength 50 Ω microstrip line with width W_0 and total length (l_1 + l_2). The feeding 50 Ω transmission line is tapped near the center of the half-wavelength resonator, so that the resonator has a narrow band response (in another word, high external Q) just as the parallel LC-resonator (L_1 and C_1).

We carry out the parallel RLC resonator (C_2, L_2, and R_L) by the inverted U-shape patch. The patch length l_p is about half a wavelength. The width W_p is adjusted to provide the radiation resistance, R_L, due to the radiating fringing field along the upper and lower edges. The slot at the bottom of the patch is preserved for gap-coupling feed.

Lastly, we integrate the patch antenna (C_2, L_2, and R_L) and the half-wavelength resonator (C_1 and L_1). About half of the resonator is inserted in the slot. The gap widths, g_1 and g_2, is adjusted to obtain enough coupling.

III. Simulation and Measurement Results

Fig. 3 shows the photograph of the fabricated antenna. The overall area, (l_p + g_1 + W_0) × W_p, is about 0.6λ_g × 0.6λ_g. where λ_g is the guiding wavelength in the substrate. With a little bit larger area compared to the regular square half-wavelength patch antenna, we achieve an antenna with the two-stage equal-ripple filtering function

The simulation was done by Ansoft High Frequency Structure Simulator (HFSS) [8], and the measurement is by Agilent 8510C Vector Network Analyzer. The measured/ simulated return loss and peak gain are shown in Fig. 4. The simulated and measured results are well-matched. Two transmission poles are at 11.9 GHz and 12.2 GHz, respectively. The passband return loss is greater than 13 dB. The antenna peak gain (total gain in +z-direction) is about 5 dBi and has a flat response within the passband.

It is revealed from Fig. 4 that in the range of 9-11.3 GHz and 13-15 GHz, the peak gain is less than -10 dBi. Note that it is a 15 dB difference from the peak gain (about 5 dBi) in the passband. The peak gain response at the band edges has a steep skirt. That is, good selectivity.

Fig. 5 illustrates the simulated and measured far-field radiation pattern (total gain) at 12 GHz, the center frequency in pass-band. The coordinate system is the same as that shown in Fig. 2. The far-field radiation patterns are similar to that of the regular square patch antenna. This antenna has 5 dBi peak gain in θ = 0° (+z-direction). The backward radiation is caused by the finite ground effect. The radiation pattern maintains the similar shape throughout the passband. The simulated efficiency of the antenna is about 70 % at the passband.

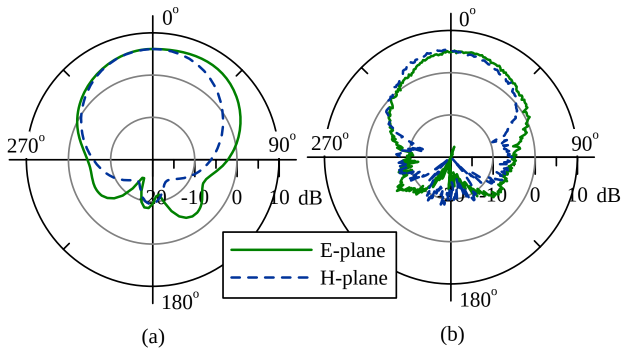

Fig. 5. (a) Simulated and (b) measured radiation pattern at 12 GHz. Solid line: E-plane (*yz*-cut). Dashed lines: H-plane (*xz*-cut). The coordinate system follows the one

IV. Simulated Current Distribution

Fig. 6 is the simulated time averaged current distribution at 12 GHz. Some physical insight can be obtained from this figure. We begin with the L-shape resonator. The current distribution forms a standing wave – the averaged current is strong at center and weak at both open ends. On the feeding section of the microstrip, the averaged current strength keeps constant, namely, a travelling wave flowing in +*x*-direction with no reflection. Thus, the structure is well-matched.

For the inverted-U shape radiating patch, most of the current distributes around the slot and on the left/right edges of the radiating patch. The current on the left/right edges flows in *y*-direction and forms a standing wave. This is similar to the current distribution of the regular square patch antenna operating at TM_{010} mode.

A small portion of the current flows on the upper edge of the inverted-U shape patch. It flows in *x*-direction and contributes to the cross-polarization radiation.

The L-shape resonator and the patch are coupled by the gap inside the slot. The current around the slot is induced by the section of the L-shape inserted in the slot, and flows in an opposite direction. The idea of the coupling section is similar to the parallel-coupled line bandpass filter. The slot between the inverted-U shape patch and the L-shape resonator forms an admittance inverter in

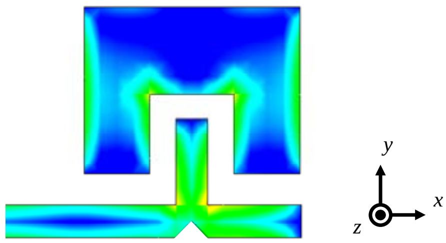

Fig. 6. Simulated current distribution at 12 GHz. The brighter region represents larger current strength.

filter design. Therefore, an extra circuit area is not needed for designing the admittance inverter.

V. Conclusions

With a second order 0.2 dB equal-ripple response and 4 % fractional bandwidth, a microstrip antenna operating at 12 GHz is proposed. The design follows the synthesis process of the bandpass filter. An edge-fed gap-coupled mechanism without suffering more circuit area is developed, and it also acts as admittance inverter in the filter design. The antenna provides good selectivity and flat in-band antenna gain response.

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