An integrated low frequency ratio wideband filtering duplex slot antenna

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Abstract: An integrated low frequency ratio wideband filtering duplex slot antenna with high isolation is proposed in this letter. The antenna consists of two layers: four circular slots are sequentially introduced between two layers, four orthogonal slotlines are etched to connect them, which are used as radiation structures; two pairs of split-ring resonators (SRRs) are inserted into two orthogonal microstrip line baluns ending in open stubs on both top and bottom layers, respectively, which is considered as the feeding network. Then, two independent broad operation bands are achieved by employing two orthogonal broadband resonator-based filtering feeding lines to excite circular slot mode. Furthermore, both filtering characteristic and polarization diversity help to improve port isolation, which contributes to frequency duplex function. The antenna is fabricated and tested. The measured results indicate that the impedance bandwidths of the lower-and-upper-band channels are 24.5% (2.29–2.93 GHz) and 17.5% (3.11–3.71 GHz), respectively. Low frequency ratio (1.05) is achieved. Port isolation is better than 42 dB and the cross polarization level is below 26 dB.

Keywords: frequency ratio (FR), broadband, filtering duplex antenna, high isolation, split-ring resonator (SRR)

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

With the rapid development of modern wireless communication systems, the requirement of antennas with integrated multiple functions has been increased dramatically. Dual-band antennas, which greatly enhance the versatility of the systems, are often used in satellite transceiver system, wireless compact handheld devices, etc. In those communication systems, the uplink and downlink channels independently occupy two separate operating bands to transmit and receive data, respectively [1]. Traditionally, a duplexer is utilized for enhancing the isolation between two channels to reduce the interference. In order to further enhance compactness and efficiency of the RF front-end system, the duplex antenna fed by two separate ports with intrinsic high isolation is introduced [2, 3, 4]. The duplex antenna, integrated the duplexer and antenna modules, will have a more extensive application.

Recently, a set of studies has been done for different types of duplex antennas, especially for highly integrated filtering duplex antennas [4, 5, 6, 7, 8, 9]. Those antennas are composed of two parts, a dual-band antenna and a corresponding filter-based feeding network. The duplex characteristic is promoted by employing the filter-based feeding network to excite the radiation antenna.

As to a duplexer, it is difficult to design a common input port to match the filter channels when the operation bandwidth becomes wider. The mutual interference is usually enhanced [10]. The structures of balanced open-circuited periodic stubs [11] and periodic hairpin lines [12] are adopted to achieve broadband duplex performance. However, it is hard to integrate them due to complex structures. Moreover, the port isolation will get a deterioration when the operation frequencies are close to each other. Thus, the manufacture of a low FR broadband duplex antenna is a challenge. The combination of polarization diversity and filtering characteristic can promote port isolation performance, which is more suitable for designing a low FR wideband duplex antenna.

In this letter, an integrated low FR wideband filtering duplex slot antenna with high isolation is proposed. Firstly, inspired by the wideband antennas [13, 14, 15, 16], a double-layer wideband slot antenna excited by a set of orthogonal microstrip line baluns ending in open stubs is designed for low frequency ratio (FR) application adopted by major communication systems. It is worth emphasizing that a dual-band antenna may not achieve low FR performance due to the limitation of the intrinsic FR. Then, a set of split-ring resonators are inserted to realize the filtering performance. The selection of resonator needs to be integrated easily. The feeding network should match the bandwidth of radiation antenna. Finally, a highly integrated filtering duplex antenna is achieved by coupling the orthogonal SRR-based filtering microstrip line baluns to circular slots. An intuitive resonator-based topology is used to illustrate the proposed duplex antenna, as shown in Fig. 1. In addition, both filtering performance and polarization diversity extremely improve port isolation. Because of the integrated multiple functions, the proposed antenna will have a good potential in the frequency division duplex systems.

Fig. 1. The equivalent resonator-based topology of the proposed filtering duplex antenna.

2 Antenna design and analyze

The geometry of the proposed antenna and detailed parameters are described in Fig. 2. Fig. 2(a) shows the top view and Fig. 2(b) shows the side view. The overall structure is printed on two substrates of F4BM 220 material with thickness of 1 mm, permittivity of 2.2. A pair of orthogonal microstrip line baluns ending in open stubs with SRR-based filters is printed on the top layer of the upper substrate, while another pair is printed on the bottom layer of the lower substrate. Between two layers, four circular slots connected by orthogonal slotlines are etched. The circular slot modes are excited by two sets of parallel feeding lines, respectively.

Fig. 2. Structure of the proposed antenna. (a) Top view (b) Side view (c) SRRs. ($L = 150$, $D_1 = 48$, $D_2 = 16$, $D_3 = 8$, $L_{slot} = 24$, $W_{slot} = 3.8$, $W_{f1} = 6.4$, $W_{f2} = 3$, $W_{f3} = 2$, $L_{d2} = 6.8$, $L_{d3} = 1.3$, $L_s = 8.2$, $W_s = 0.3$, $g_1 = 0.2$, $g_2 = 0.24$, $g_3 = 0.28$, $M_s = 0.4$, $L_u = 6.7$, $W_u = 0.26$, $q_1 = 0.24$, $q_2 = 0.58$, $q_3 = 0.22$, $M_u = 0.4$) (Unit: mm)

The antenna design can be divided into two steps:

First step: a double-layer wideband slot antenna excited by a set of orthogonal microstrip line baluns ending in open stubs is designed, which is shown in Fig. 3(a). This antenna can be analyzed as a wire antenna, where the wire is formed by the metallization around the slot. A pair of opposite currents are excited on both sides of the slotline, in the feeding point. The broadband performance is primarily decided by the shape of the slot and the metallization length and width around the slot. Fig. 3(b) indicates that simulated -10 dB impedance bandwidth is 35% from 2.5 GHz to 3.56 GHz and port isolation is about 33 dB. Some reports have introduced that the port isolation can reach 40 dB by the differential feeding. In [17], a dual-polarized patch antenna with high isolation (up to 40 dB) is presented. A Wilkinson power divider and a half-wavelength delay line are used

to realize differential excitation for horizontal polarization. A single resonant annular-ring slot is used as a dual-slot feed system with a 180° phase shift for vertical polarization. However, the design is a little complicated. In addition, the introduction of meandering probes makes the fabrication complicated. In [18], two dual-polarized patch antennas achieve high isolation and low cross-polarization levels by using simple 180° ring hybrid coupler. In [19], higher interport RF isolation and excellent polarization purity are achieved by adding a 3 dB/180° ring hybrid coupler on the basis of the antenna proposed in [18]. However, the bandwidths of the antennas in [18, 19] are only 2%. In our work, the design is simple and the fabrication is easy. Furthermore, the bandwidth performance is pretty good.

Nevertheless, it is difficult to separate the operation bands completely by adjusting the radiation structure and the feeding line because new operation bands will be introduced. The out-of-band rejection of filter can solve this problem. Thus, the method of designing filtering feeding network is adopted to achieve duplex characteristic.

Fig. 3. (a) The top view of the proposed wideband antenna; (b) Simulated |S|-parameters of the proposed wideband antenna

Second step: SRRs are inserted to microstrip line baluns for serving as different filtering channels due to its simple structure and bandwidth adaptability. As to SRR, the position, where gaps of rings are on the opposite sides of X axis, decides that the coupling between two SRR units is the combination of magnetic coupling and electrical coupling. Its equivalent circuit is a parallel form of the magnetic coupling and electrical coupling circuits [20]. The Y parameter matrix of the electrical coupling circuit can be generated as

$$Y = \begin{bmatrix} j\omega C & -j\omega C_m \\ -j\omega C_m & j\omega C \end{bmatrix} \quad (1)$$

The Z parameter matrix of the magnetic coupling circuits can be expressed as

$$Z = \begin{bmatrix} j\omega L & j\omega L_m \\ j\omega L_m & j\omega L \end{bmatrix} \quad (2)$$

L and C are the self-inductance and self-capacitance of SRR, and L_m and C_m are the mutual inductance and mutual capacitance between adjacent SRRs. As shown in

Fig. 4, the equivalent circuit is obtained by the two-port network theory. T - T' represents the symmetry plane of electrical coupling and magnetic coupling. The odd- and even-mode methods can be used to analyze the equivalent circuit. The odd-mode resonant frequency f_e , the even-mode resonant frequency f_m and the coupling coefficient M_{12} can be expressed as

$$f_e = \frac{1}{2\pi\sqrt{(L - L_m)(C + C_m)}} \quad (3)$$

$$f_m = \frac{1}{2\pi\sqrt{(L + L_m)(C - C_m)}} \quad (4)$$

$$M_{12} = \left| \frac{f_m^2 - f_e^2}{f_m^2 + f_e^2} \right| = \left| \frac{LC_m - CL_m}{LC - C_mL_m} \right| \quad (5)$$

The self-inductance C mainly depends on the gap g_2 . The self-inductance L is approximated by a single ring with averaged side length $(L_s - g_3/2 - Ws)$ and width Ws . The distance g_1 between two SRR units have a great effect on L_m and C_m .

Fig. 4. The equivalent circuit of SRR combined magnetic coupling and electrical coupling.

Due to high port isolation performance, it has a slight effect on another channel when one channel changes by adjusting the feeding line. Thus, the parameters of SRR1 are studied, independently. Fig. 5 illustrates the S-parameters of Port 1. From Fig. 5(a), we can find that the distance g_1 has a significant impact on impedance matching and impedance bandwidth. When the distance g_1 decreases, the resonant frequencies of the magnetic coupling mode and electrical coupling mode separate from each other. Therefore, the impedance bandwidth is improved obviously and the impedance matching still satisfies device requirements. Besides, the frequency selectivity and out-of-band rejection performance will get deterioration. Fig. 5(b) shows that a little influence on impedance matching is produced by the gap distances g_2 . That's because it has a low effect on the coupling coefficient. In addition, the operation bandwidth will be slightly shifted with the decreasing g_2 .

Finally, the highly integrated low FR filtering duplex antenna is achieved when the circular slot mode is excited by coupling the orthogonal SRR-based filtering microstrip line baluns to circular slots. The electric field distributions for Port 1 at 2.6 GHz and Port 2 at 3.4 GHz are shown in Fig. 6. From the figures, it shows that

little energy is leaked into another port when the input power is imported into one port. This means high port isolation can be achieved.

Fig. 5. Simulated reflection coefficients of Port 1 with varying (a) g_1 , (b) g_2 .

Fig. 6. The electric field distribution: (a) Port 1 at 2.6 GHz; (b) Port 2 at 3.4 GHz.

3 Fabrication and measurement

High Frequency Structure Simulator (HFSS) has been used to optimize the proposed antenna. The finally optimized dimensions of parameters are given in Fig. 2. To validate the design and analysis, an antenna prototype shown in Fig. 7 is fabricated. Agilent N5230 vector network analyzer is used to measure the S-parameters of the proposed antenna while the radiation patterns are measured in an anechoic chamber. In all measurements, when one port is excited, another port is matched with a 50 Ω load.

Fig. 7. Antenna prototype: (a) Feeding structure on top surface; (b) Radiation structure on middle surface.

The simulated and measured $|S|$ -parameters are plotted in Fig. 8. When port 1 is excited, the measured -10 dB impedance bandwidth is achieved from 2.29 to 2.93 GHz (FBW 24.5%) and the simulated -10 dB impedance bandwidth is realized from 2.31 to 2.96 GHz (FBW 22.8%). When port 2 is excited, a measured band from 3.11 to 3.71 GHz (FBW 17.5%) is obtained and the simulated band is from 3.07 to 3.73 GHz (FBW 19.4%). The insertion loss and bandwidth adjustment from SRR help to broaden the bandwidth. Therefore, the working bandwidth of the duplex antenna is wider than the broadband antenna mentioned in section II (simulated FBW 35%). The measured results are basically consistent with the simulated results. From the measured bands, it can be found that the minimum FR is 1.05.

As for port isolation, the simulated result increases from 33 dB to 44 dB when the SRR structure is inserted. The improvement is obvious. The measured result is 42 dB. A little difference may be attributed to the air gap between the two layers, the practical SMA connectors and the experiment tolerance.

Fig. 9 shows the simulated and measured realized gains. The antenna has flat gains of around 7.6 dBi in the lower operation band and 7.3 dBi in the higher band, respectively. The rate of realized gain doesn't decline as sharp as it supposed to be. There are two main reasons. Firstly, taking full consideration of the bandwidth and out-of-band rejection performance, we have looked for suitable parameters. In other words, bandwidth expansion is at the expense of filtering performance. Secondly, due to the low frequency ratio, the gains drop unnoticeably out of the two bands. The completed job mainly concentrates on realizing the performance of wide bandwidth and low frequency ratio. The simulated and measured radiation patterns of lower and higher operation frequencies at 2.6 and 3.4 GHz are presented in Fig. 10. The dipole modes are excited at both operation frequencies. Good XPLs, better than 26 dB, are achieved for the two dipole modes. Excellent agreement is promoted between the measured and simulated co polarization components. However, the measured cross polarization has a distinction from simulated one. It is mainly contributed by the air gap between two layers and the SMA connectors.

Table I compares the proposed duplex antenna with other reported duplex antennas. In [4, 5, 7, 8], due to the limitation of operation bands of the dual-band antennas, the relative impedance bandwidths of the duplex antennas are about 5%. In [5], high-order mode is excited to realize the broadside radiation, which limits the adjustment of the frequency ratio. In [6], a broadband patch antenna is designed based on T-shaped probe. However, the air gap of the antenna leads to the high-profile ($0.09\lambda_0$). The fabrication of the antenna is difficult. In this work, the proposed antenna features a wide bandwidth, low profile ($0.02\lambda_0$), low FR and high port isolation.

Fig. 8. Simulated and measured $|S|$ -parameters of the proposed duplex antenna.

Fig. 9. Simulated and measured gains of the proposed duplex antenna.

Fig. 10. (a) E- and H-plane radiation patterns at 2.6 GHz. (b) E- and H-plane radiation patterns at 3.4 GHz of the proposed duplex antenna.

Table I. Comparison with previous works

Ref.	Polarization	f1, f2 (GHz)	Isolation (dB)	Relative impedance bandwidth	Minimum FR
[4]	Single	2.6, 2.88	32	5%, 4.2%	1.06
[5]	Single	2.45, 5.25	21	4.5%, 5.5%	2.05
[6]	Single	2.06, 2.6	45	10.6%, 6.9%	1.15
[7]	Dual	5.2, 10	20	3.8%, 6%	1.81
[8]	Dual	4.86, 5.9	28	4.8%, 5.1%	1.15
This work	Dual	2.6, 3.4	38	24.5%, 17.5%	1.05

4 Conclusion

In this letter, an integrated low FR wideband filtering duplex antenna with high isolation is proposed. A wideband slot antenna coupled by a pair of orthogonal microstrip line baluns is designed firstly. Then, two dual-mode resonators SRR are loaded on the baluns as feeding network to form two separate filtering channels. Finally, duplex characteristic is achieved as the circular slot mode is excited by the filter-based feeding network. The measured -10 dB impedance bandwidths for upper band and lower band are 24.5% and 17.5%, respectively. Low FR (1.05) is achieved. The port isolation is 42 dB and the cross polarization level is below 26 dB. Due to the performances of wide bandwidth, low FR, duplex and high isolation, the proposed antenna has a potential candidate for various mobile communication systems.

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