Substrate Integrated Waveguide Band-pass Filter with Coupled Complementary Split Ring Resonators

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Abstract

This paper presents a design of bandpass filter applied to ultra-wide band RFID system (IEEE standard 802.15.4f), by combining SIW's high-pass property with the loaded CSRR played as low pass filter. The working mechanism of CSRR, single-cell CSRR on SIW structure and SIW-coupled CSRR pair is introduced. The principle of CSRR equivalent circuit of SIW transmission line and SIW-coupled CSRR pair is analyzed and achieves good agreement with configuration of the structure. The resonant frequency of CSRR is set at transmission zeros at stopband. The measured 3 dB passband bandwidth is 5.5-8.25 GHz with insertion loss less than 2dB. The stopband extends from 8.5 GHz to 11.5 GHz with better than 30 dB rejection.

1. Introduction

In recent years, some special electromagnetic structures, such as EBG, SRR, and complementary split rings resonators (CSRR), etc, have been introduced to improve the performances of the microwave circuits[1]. The complementary split ring resonators (CSRR) can provide a negative effective permittivity in the vicinity of its resonant frequency and produces sharp rejection band along with property of small electrical compact size[2].

On the other hand, the Substrate Integrated Waveguide (SIW) is synthesized by placing two rows of metallic via holes in a substrate[4]. It has advantages of low loss, high Q-factor like conventional rectangular waveguide and has been demonstrated to provide an attractive solution to low-cost microwave and millimeter circuits[5].

Ultra-wide band RFID system, due to its property of wide channel bandwith, high data rate transmissions and low power consuming, has been applied to remote sensoring and accurate localization and Electronic Toll Control[3].

The purpose of this paper is to discuss the performance of the CSRR structure etched in substrate integrated waveguide, and to get the equivalent circuit model of the structure and use it to design a wide band-pass filter of 6.25-8.25GHz passband bandwidth with sharp cutoffs, meeting the required channel frequencies specified by IEEE Standard 802.15.4f.

2. Design of SIW filter Loaded by CSRR Structure

Substrate Integrated Waveguide (SIW) is integrated waveguide-like structures fabricated by using two rows of conducting cylinders or slots embedded in a dielectric substrate that electrically connect two parallel metal plates[3]. The field distribution in an SIW is a TE10 like mode, similar to that in a conventional rectangular waveguide, and like the conventional rectangular waveguides, the SIW demonstrates typical high-pass characteristics. The detailed description on the propagation characteristics of SIW including formula of effective width, calculated propagation constants and cutoff frequency in TE10 mode has been presented in [4-6]. In order to better match the microstrip feed line and the waveguide, a back-to-back tapered-line transition is used in the SIW design.

The split ring resonators (SRR) is a pair of two coplanar broken metal rings with a high quality factor at microwave frequencies. When they are excited by an external time varying magnetic field applied parallel to the ring axis (see Fig. 1), an electromotive force around the rings is generated giving rise to current loops in the rings. These current loops are closed through the distributed capacitance between the concentric rings. According to this, the SRR behaves as an externally driven LC circuit and being the reactive elements and accounting for losses. The calculation of inductance of the ring, mutual inductance of the two rings, the effective capacitance and the resonant frequency of the SRR is descripted in [7]. By invoking the concepts of duality and complementarity, the resonant frequency of the CSRR（the negative image of the SRR), should be approximately the same with the SRR[7-8]. In order to increase the coupling coefficient, we use rectangular-shaped CSRR, replacing 4*b* (*b* is the square length) with the closed ring length for the search of CSRR resonant frequency.

Single-cell CSRR on SIW structure, as presented in Fig.1(b), is etched on the top surface to preserve the integrity of the bottom plane. The adoption of such configurations is partially based on the field distribution inside the waveguide. The electric field for TE_{10} mode within SIW is perpendicular to the surface and ground. The direction of the magnetic

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field is parallel to the waveguide surface and perpendicular to the sidewalls. The CSRR, excited by anaxial electric field, behaves as an electric dipole and is similar to that of the original SRR excited by an axial magnetic field, providing in both cases a rejected frequency band around the resonant frequency of the particle[9].

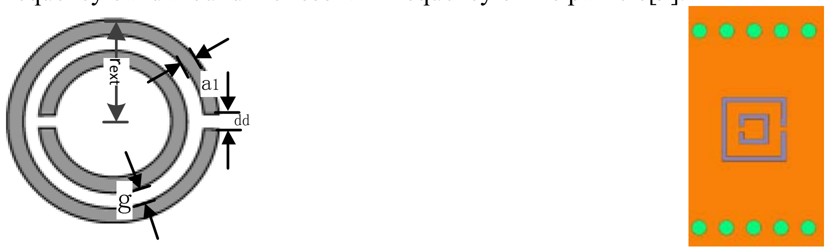


Fig.1 (a)topology of SRR (b) topology of Single-Cell CSRR structure on SIW

In [9], the transmission responses of SIW-coupled CSRR pair, with different direction of the split of the outer ring(face-to-face, back-to-back, and side-by-side) has been studied. The electric field reaches its maximum in the vicinity of the gap and the magnetic field reaches its maximum around the opposite part of the split ring. The two rings side-by-side reversely arranged(Fig.2(a)) is chosen for our work on which condition both electric and the magnetic couplings occur[9], obtaining a good filtering response with two transmission and transmission zeros in the upper band and cause resonant frequency shifting[10].

Fig. 2(b) shows the schematic of the equivalent circuit model of SIW-coupled CSRR pair. Material losses in the models are all neglected. The arrays of the vias can be considered as inductance L_v and the CSRR can be modeled as a resonator tank with inductance (L_r) and capacitance (C_r). L_c, C_c indicate the coupling between SIW transmission line and CSRRs, and L_s , C_s denote the combination of electric and magnetic coupling between the CSRRs. Fig. 2(c) and (d) presents the configuration and equivalent schematic circuit model of a piece of SIW transmission line. It consists of the arrays of the vias inductance L_d, in parallel with the capacitive coupling C_d by the center patch of the resonator and the ground and two-wire transmission distributed inductance L_{line}.

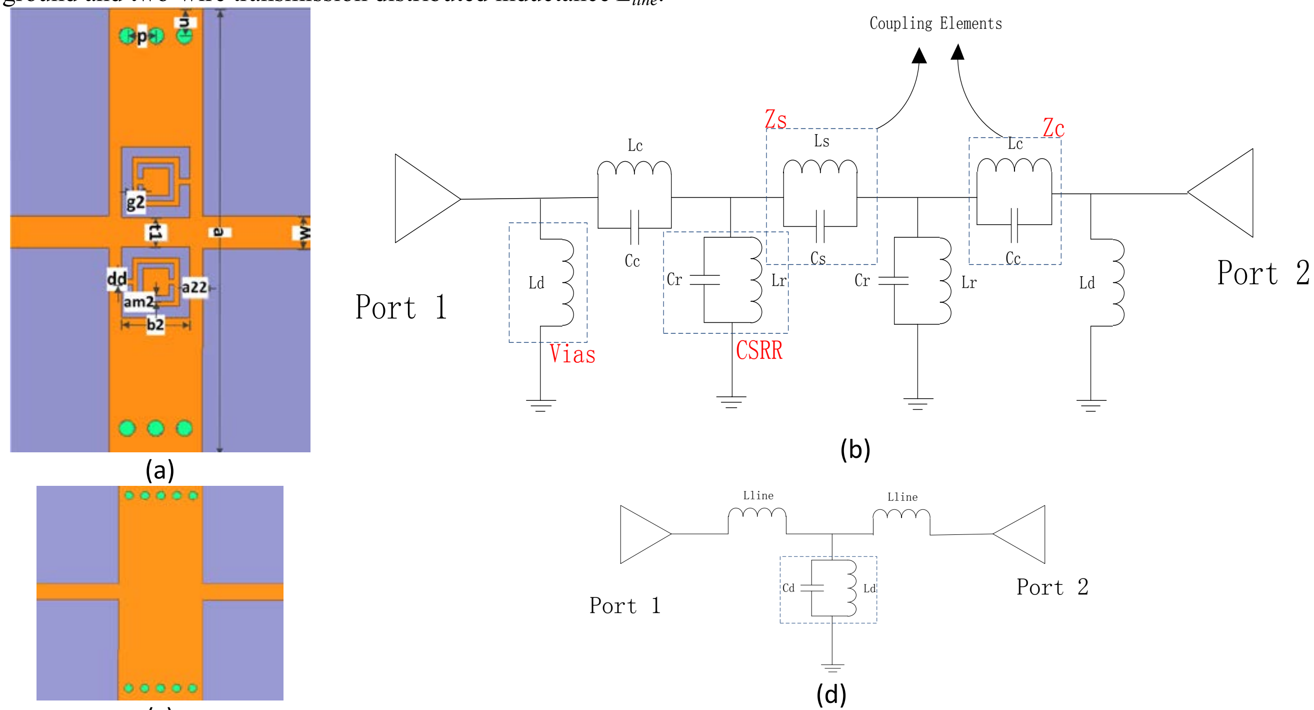
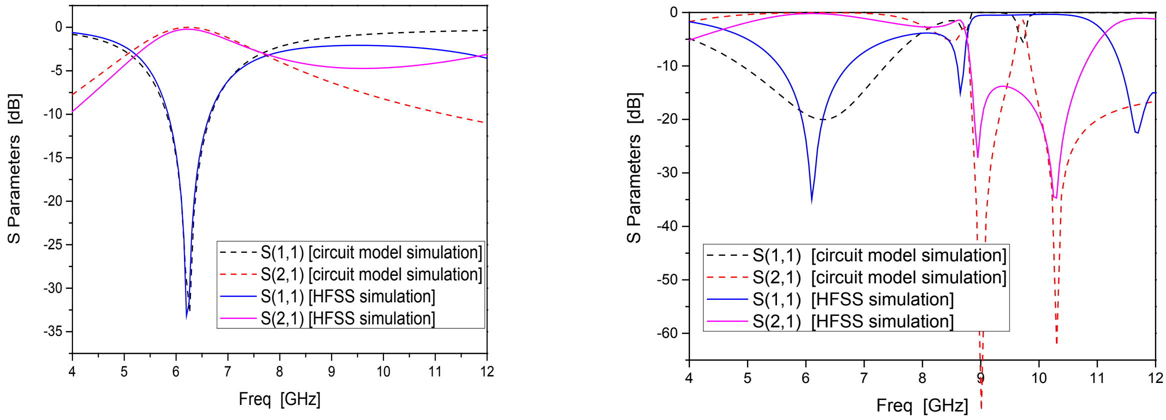


Fig.2 (a)Configuration of SIW-coupled CSRR pair (b) Equivalent circuit model of SIW-coupled CSRR pair (c)Configuration of SIW Transmission line (d)Equivalent circuit model of SIW transmission line

The width of the SIW, a, is set to 14.5 mm to achieve cutoff frequency of 5.77 GHz. Additionally, three CSSRs cells with resonant frequency of 9GHz, 10.25GHz, and 11.5GHz are used to generate transmission zeros at the stopband to implement the required high out-of-band rejection from 9 to 11.5 GHz. This can be achieved by appropriately choosing geometry dimensions of CSRRs cell. Theoretical calculation in [7] indicates that external radius r_{ext} and gap width g governs the inductance of the ring (L_r) The slit width dd and strip width a_1 controls effective capacitance (C_r) of the SRR. The values of electric parameters, L_v, L_c and C_c can by configuration using the method presented in [11]. The initial physical configuration of the filter can be determined by equivalent circuit model.

Fig. 3 presents the HFSS and circuit model simulations of SIW-coupled CSRR pairs(function as a low pass filter) and SIW transmission line (function as a high pass filter) ,with the values of the lumped elements depicted in figure caption. As shown in Fig. 3(b), two transmission zeros are introduced by two coupling, CSRR with SIW and two CSRRs respectively . Good agreement between circuit model and physical configuration has been achieved. Then these two units are cascaded to make up the proposed microstrip band-pass SIW filter loaded by CSRR structure.



(a) (b)

Fig.3 (a) Transmission responses by circuit model and full wave simulation of SIW transmission line. The electrical parameters are C_d=2pF, L_{line}=0.88nH, L_v=0.4nH. The geometrical parameters for the unit cells are identical with those in Table 1.

(b) Transmission responses by circuit model and full wave simulation of SIW-coupled CSRR pair. The electrical parameters are L_d=4nH, L_c=0.2pF, C_c=1.56nF, L_r=2.61nH, C_r=0.26pF, L_s=0.21nH, C_s=1.14pF

3. Simulation and Measured Results

In order to obtain a sharp cutoff with wide and good out-of-band rejection, a SIW-BPF constituted with five cascaded CSRR is designed. The final optimal physical configuration and photograph of the proposed filter are illustrated Fig. 4 and Fig. 5 and the geometrical parameters is presented in Table 1. The filter is designed and optimized with HFSS™ and fabricated with Rogers RO4003 substrate with a relative permittivity of ε_r = 3.55 and a thickness of 0.508 mm. The filter was measured with an HP-8720ET network analyzer.

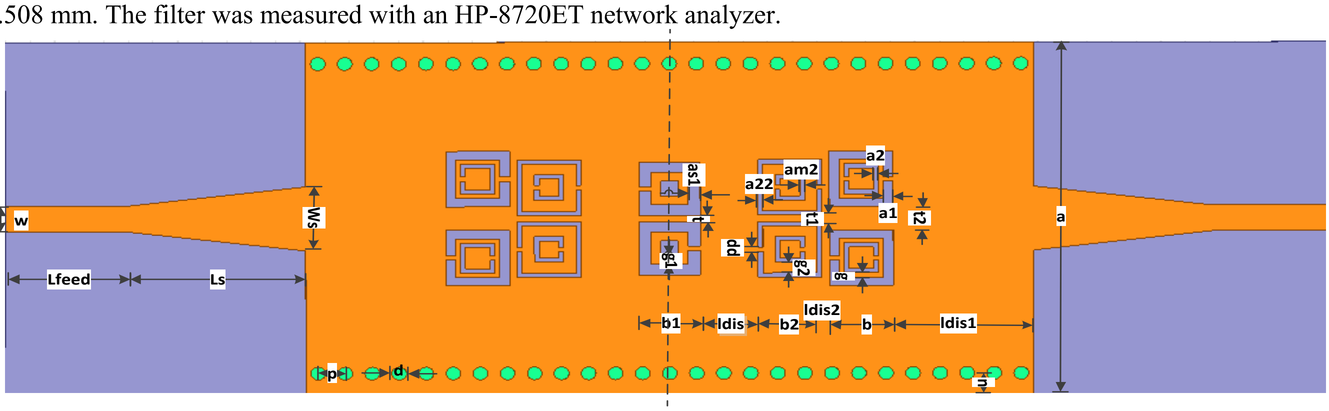


Fig. 4 Physical Configuration of SIW-CSRR band-pass filter

TABEL 1 GEOMAETRICAL PARAMETERS OF THE BPF SAMPLE (UNIT:mm)

a	a_1	a_2	d	p	w	W_s	L_s	L_{feed}	a_{22}	a_{s1}	a_{m2}	dd
16.5	0.4	0.2	0.6	1.1	1.2	3	7.3	5	0.2	0.5	0.2	0.2
l_{dis}	l_{dis1}	l_{dis2}	g	g_1	g_2	b	b_1	b_2	t	t_1	t_2	n
2.35	5.8	0.3	0.2	0.4	0.5	2.6	2.5	2.6	0.3	0.3	1.1	1

As shown in Fig.6, the filter provides lower than 16.5dB return loss for whole passband (over 6 to 8.25 GHz). The measured 3 dB bandwidth is 2.75 GHz (5.5-8.25 GHz).The insertion loss is less than 2dB through 5.5 GHz to 8 GHz including the feed lines and SMA connectors. A small frequency shift is observed due to the fabrication and loss tangent of substrate by comparing the simulated and measured frequency response. The measured stopband extends from 8.5 GHz to 11.5 GHz with better than 30 dB rejection.

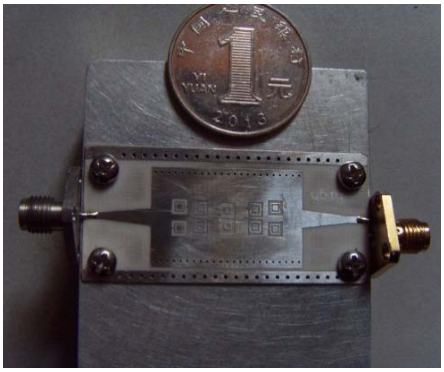


Fig.5 The photograph of fabricated filter

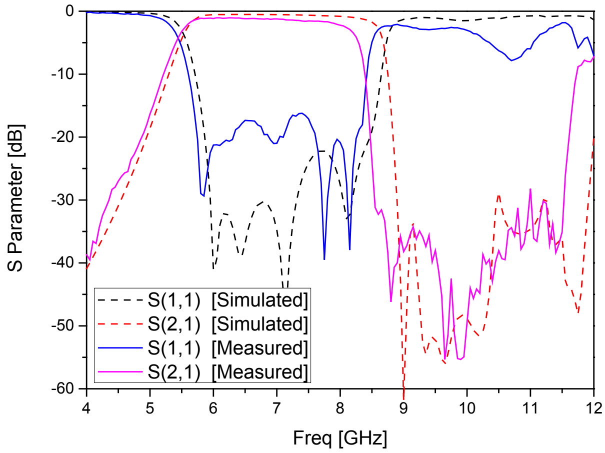


Fig. 6 The simulated and measured results of the proposed filter

4. Conclusion

A compact microstrip band-pass SIW filter loaded by CSRR structure has been analyzed and designed. The experimental results implies the deep rejection band with sharp cutoffs, with low return losses and wide passband bandwidth is achieved .The proposed type achieves great filtering properties for UWB-RFID applications.

5. References

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