A Low-loss Coaxial Comb-line Filter Design and Implementation for Aircraft Autopilot FMCW Radar Altimeter

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Received: 2015/9/15 Accepted:2015/11/22

Abstract

Pulse or FMCW altimeters are used for height or distance measurement. For both types, a radio frequency signal is sent and after few micro seconds the reflected signal from the ground or sea is received and then by signal analysis the height can be measured. Because of wide frequency bandwidth of mixer in receiver and for better sensitivity, frequency modulation, jamming and noise, a narrowband low insertion loss bandpass filter should be designed. In this paper a new structure $\frac{\lambda_g}{4}$ stepped impedance resonator (SIR) narrowband bandpass filter is proposed that has special specifications such as %4.5 tunable bandwidth (%3 up to %7), sharp and wide stopband frequency characteristic, less than 0.7 dB insertion loss in passband and more than 80 dB rejection in stopband. With new coaxial resonators the seven pole Chebychev bandpass filter is designed and fabricated with more than %15 frequency tuning capability. Good agreement between measured and simulated results validates this design process.

Keywords: Narrowband filter, Coaxial filter, Altimeter system, Multilayered SIR.

Introduction

Coaxial bandpass filters have important role in communications, since they have compact size, low insertion loss, wide stopband and sharp frequency characteristic, and are low-cost. They are also suitable for high power RF signals because all parts of the filters' structures are made of metal [1-2].

Various coaxial comb-line filters and different coupling ways to design them are published by many writers [3-8]. But better frequency responses and spurious rejection can be obtained by new structures, optimization techniques and commercial software. These useful compact low-cost structures are used in communication companies and wireless communications and these research fields are selected as important subjects by universities or companies [9-17].

In some references almost similar frequency resonators were designed, but with combination of the new coaxial resonators and iris filter structure that creates bigger tuning capacitors and inductors, wider frequency tuning and frequency bandwidth tuning are achieved [18].

Moreover, altimeters are used in military or commercial applications. The two kinds of altimeters are:

a) Pulse altimeters: In this method, an RF wave is modulated with a pulse and altitude is measured by measuring the time interval between sent and received signal. Disadvantages of this method are: high peak power, low altitude resolution and some limitations in low altitude measurement.

b) FMCW altimeters: In this method, a frequency modulated continuous wave is used that is modulated with a periodic ramp signal.

By using frequency modulation, transmitted and received frequency of the signal is different and by measuring this and obtaining the difference component, we can measure the altitude.

The following figure is a block diagram of the FMCW altimeter (Figure 1). Frequency of the altimeter is $4.3 \pm 0.15 GHz$, so we need a sharp band-pass filter (comb-line) to omit unwanted frequencies, noises and jamming.

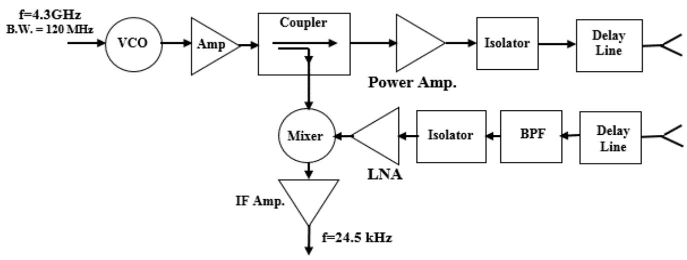

Fig.1: FMCW altimeter system block diagram.

Meanwhile, without using BPF filter block in the altimeter and because of frequency leakage, any spurious or unwanted frequency can enter the mixer and produce the intermediate frequency (about 25 kHz). This filter must remove the leaking from the mixer, as well as its image and it must also pass the received signal with no effect.

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This paper is organized as follows. The investigations of SIR, noise calculation and design of filter is presented in section 2. By these investigations, the seven pole Chebychev bandpass filter is simulated and fabricated in section 3. Finally the conclusions are drawn in section 4.

Filter Design

As depicted in Figure 1, the frequency bandwidth of the designed altimeter is about 200 MHz that can measure altitude up to 2000 meters and the center frequency is 4.3 GHz that is a common frequency in altimeter systems. In 0.8 second, the frequency sweeps from 4240 MHz to 4360 MHz and in this time signal can be sent to the ground or sea and can be received from them about 4900 times but commensurate to the altitude, the frequency sweep time changes (from about 1-20 microseconds and $\frac{120MHz}{4900} = 24.4898\text{kHz} \approx 24.5kHz$). Since the received signal is mixed with a coupled local oscillator signal from the transmitter (as is depicted in Figure 1) any unwanted or spurious signal can be a reason for system faults or less sensitivity and accuracy and so the altimeter cannot be locked in accurate and true altitude.

The sensitivity of the receiver must be better than at least -124dB and any noise and frequency interference can reduce sensitivity of the receiver. The thermal noise power can be calculated as follows (receiver bandwidth = 1 kHz and worst cases were considered in defaulted values):

$$N = N_0 + NF \tag{1}$$

$$N_0 = KTB$$

$$N = KTB_0 + NF$$

$$NF = L_{ANTENNA} + L_{CABLE} + L_{ISOLATOR} + NF_{LNA} + L_{MIXER}/G_{LNA} \tag{2}$$

$$N_0 = -144dB \quad , \quad L_{ANTENNA} = 2dB \quad , \quad L_{CABLE} = 4dB$$

$$L_{ISOLATOR} = 0.5dB \quad , \quad NF_{LNA} = 2dB$$

$$L_{MIXER}/G_{LNA} = 7/10 \approx 1dB \quad \Rightarrow \quad NF = 9.5dB \approx 10dB$$

$$N = KTB_0 + NF = -134dB$$

So, without any other noises and spurious, we can obtain this sensitivity.

Figure 2 shows the best filter design selection for any frequency bands and we can see that a good selection is coaxial filters that are compact, have narrow frequency bandwidth and can be best for high power systems.

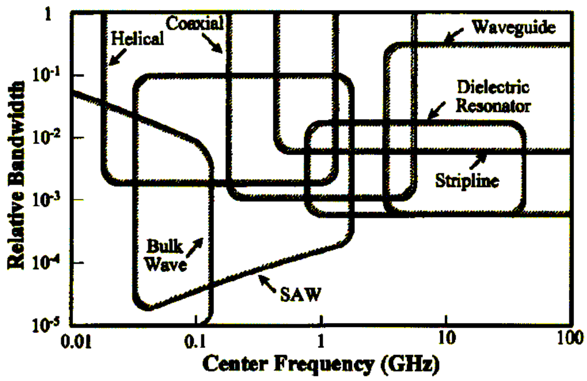


Fig.2: All kind of microwave filter design [2].

As we know, SIRs are TEM or quasi-TEM resonators that are combination of more than two different characteristic impedances. There are 3 traditional types of SIRs, a) $\frac{\lambda}{4}$ type, b) $\frac{\lambda}{2}$ type and c) λ type [2]. For designing a compact comb-line bandpass filter with center frequency of 4.3 GHz and bandwidth 200 MHz, we select $\frac{\lambda}{4}$ type resonators.

Since the frequency of the filter can be changed and due to DC current and power limitations, the structure must pass some quality specifications. The desired filter must be narrowband, capable of frequency tuning and have low insertion loss with matched input and output ports, so special SIRs should be designed. Moreover, for better frequency tuning and coupling, we need a new structure that lets us more degree of freedom for optimization, tuning and coupling of fundamental mode and damping of higher order modes. The proposed structure, equivalent circuit model, quality factor and resonance frequency of the proposed SIR are shown in Figures 3-6, respectively. The proposed multilayered SIR has better frequency tuning capability and coupling because of more efficient and bigger coupling and gap capacitors and coupling inductors (Figure 4). The resonant frequency of this SIR structure is about 4-4.6 GHz and higher order modes are much higher than this frequency (15.2 GHz, 16.6 GHz, 18 GHz ….)

The resonance condition for this structure can be calculated as follows ($Y_{in} = 0$):

$$Y_{in} = jY_{02}\frac{Y_{02}\tan\theta_1\tan\theta_2 - Y_{01}}{Y_{02}\tan\theta_1 - Y_{01}\tan\theta_2} + \frac{1}{Z_1 + Z_2} \tag{3}$$

Where:

$$Z_1 = \frac{1}{jC_t\omega + \frac{1}{jL_R\omega}} \tag{4}$$

$$Z_2^{-1} = Y_2 = jY_{06}\frac{Y_{06}\tan\theta'\tan\theta_6 - Y'}{Y_{06}\tan\theta' - Y'\tan\theta_6} \tag{5}$$

And:

$$Y' = Y_{04} + Y_{05} \tag{6}$$

Also the capacitor will be calculated as:

$$C_t = C_1 + C_2 + C_3 + C_R \tag{7}$$

And:

$$C = \varepsilon_0\varepsilon_r\frac{A}{d} \tag{8}$$

Where:

ε_r = Relative dielectric permittivity.

ε_0 =Permittivity of free-space.

A = Area of the surface adjoining the sidewalls.

d = Distance between surfaces.

L_R = Equivalent resonance inner inductor.

C_R =Equivalent resonance inner capacitor.

C_t =Total capacitor.

C_1, C_2, C_3: Parallel plate capacitors.

$C_{Tune} = C_3 + C_R$.

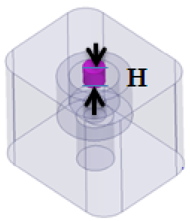
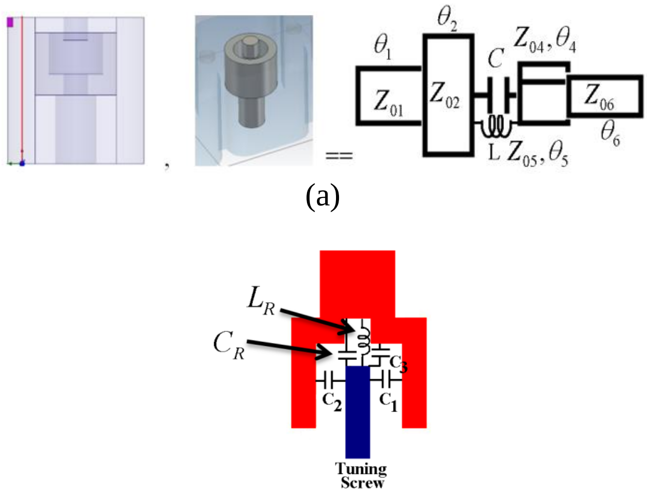


Fig.3: Proposed SIR structure.



(a)

(b)

Fig.4: Multilayer SIR and its circuit model.

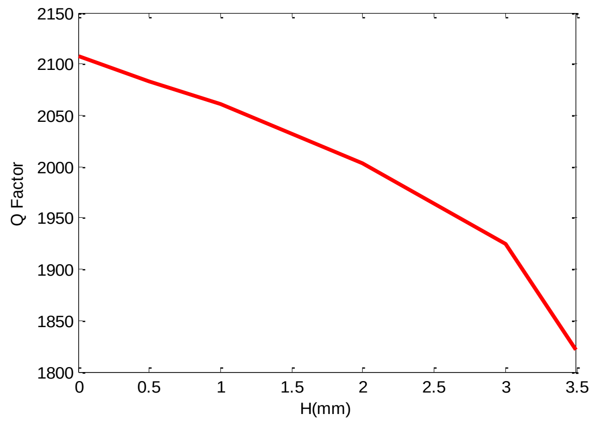


Fig.5: Q factor of proposed SIR.

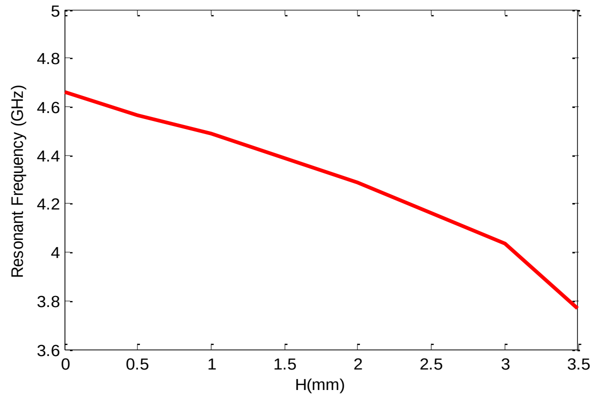


Fig.6: Resonance frequency of proposed SIR.

However, couplings between SIRs change the matching and ports' impedances and also frequency bandwidth of the structure. For better coupling structure design, the designed combination of coupling walls and coupling screws were used, so the frequency bandwidth of the filter can be changed. The coupling coefficient is achieved by placing a perfect electric conductor wall, and a perfect magnetic conductor wall between resonators and the equation for calculating the coupling coefficient is [19-22]:

$$|k| = \frac{f_e^{\,2} - f_m^{\,2}}{f_e^{\,2} + f_m^{\,2}} \tag{9}$$

Where f_e and f_m are the two eigenmodes of the SIR. These frequencies are obtained by eigenmode solver of an electromagnetic simulator [23]. The electric and magnetic fields are shown in Figure 7.

Figure 8 shows the coupling structure between two adjacent resonators which are composed of coupling screw and coupling wall. As it can be seen in Figures 9 and 10, when W reaches to optimum value (7 mm) and the length of coupling screw increases, coupling of higher order modes decreases while the coupling of fundamental mode

increases. Obtaining better frequency response and rejection of higher order modes are the results of using this coupling scheme. Therefore, electromagnetic couplings are mostly done by decoupling walls and screws while center frequencies of SIRs are dominantly tuned by frequency tuning screws.
This combine filter was designed by the general bandpass filter design method by admittance inverters and shunt resonators [20]. The filter is designed by general design method of bandpass filters with TZs and because of high quality factor of the resonators, the responses are close to ideal.

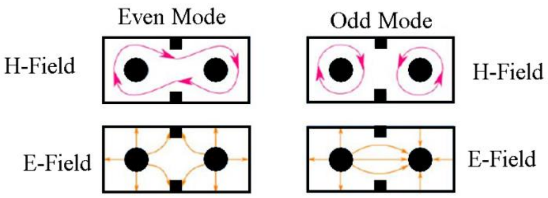
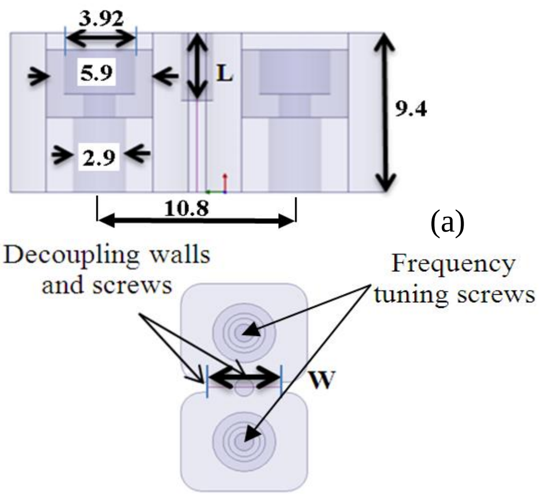


Fig.7: Even and Odd modes.



(b)
Fig.8: a) Decoupling walls and screw (side view), b) coupled SIRs (dimensions in mm) and frequency tuning screws (top view).

Simulation and Measurement Results

Finally the filter is designed and fabricated and simulation and measurement results are shown in Figures 11-16. As are depicted in these figures, the insertion loss is more than -0.7 dB and this filter has wide rejection band (the rejection band is at minimum up to 13 GHz and the rejection value is more than 80 dB). The manufactured filter is covered by gold for improving conductivity. The filter is tuned by “time domain filter tuning technique” prepared by Agilent technologies’ 8722ES network analyzer [24-25]. The tuning capability of the filter is shown in Figure 15 and is done by tuning screws and also coupling screws, because each screw can change coupling coefficients and matching while tuning screws affect mostly on center frequency of the filter. Also the bandwidth of the filter can be changed with coupling screws about %3 to %7. Figure 11 shows the equivalent circuit model for the coaxial SIR filter. The resonators are modeled with parallel capacitors and inductors, also couplings are modeled with series inductors.

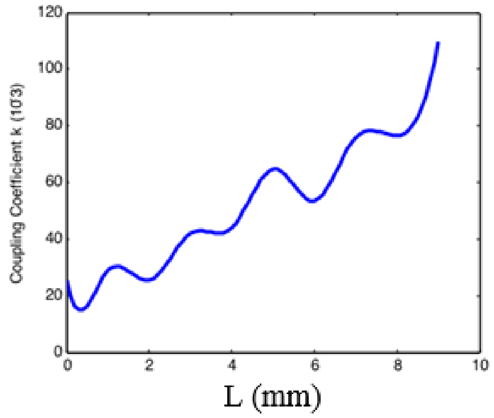


Fig.9: The coupling coefficient for W=6.9 mm for fundamental mode.

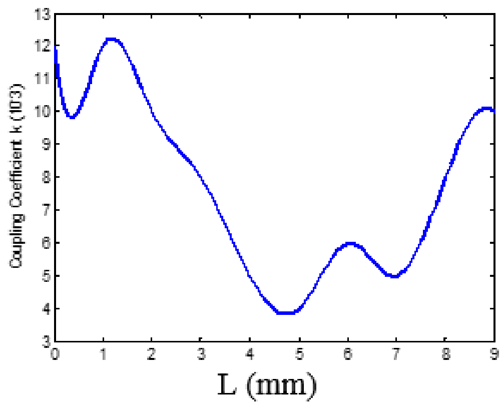


Fig.10: The coupling coefficient for higher order modes with optimum width (W=7 mm).

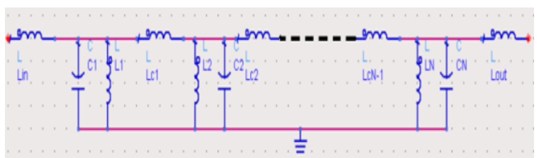


Fig.11: Equivalent circuit for the coaxial filter.

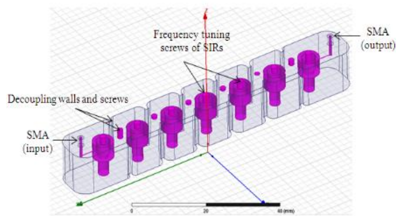


Fig. 12: Simulated filter by HFSS with proposed decoupling method with frequency tuning screws.

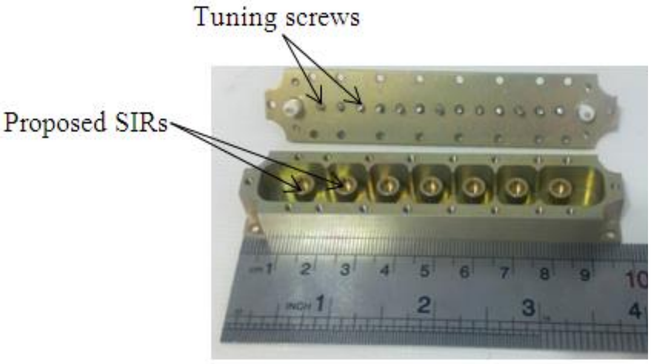


Fig. 13: Manufactured filter.

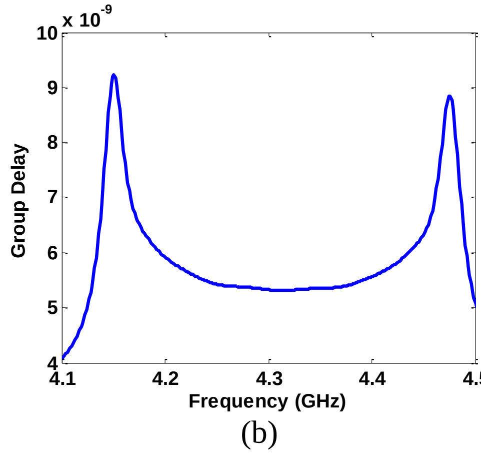


Fig. 14: Simulation results (HFSS); a) Frequency responses, b) Group delay values.

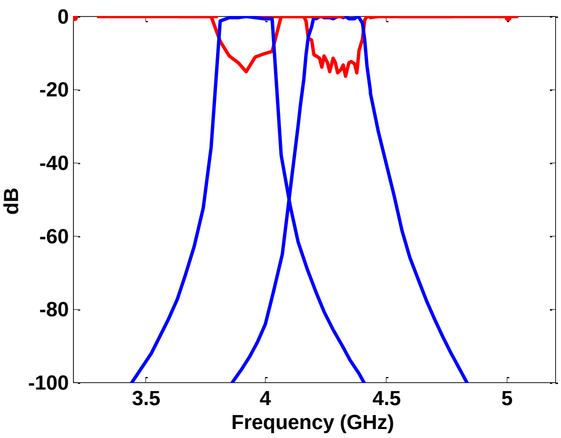


Fig. 15: Frequency responses of the filter simulated by HFSS and tuned with tuning screws.

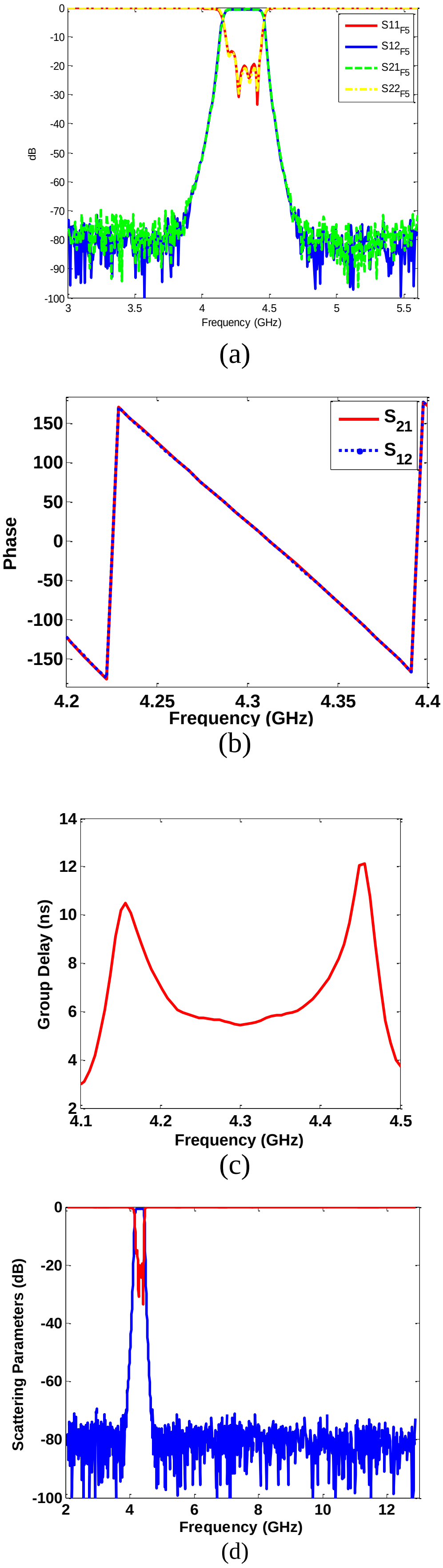


Fig. 16: Measured results of final designed filter; a) Narrowband scattering parameters, b) S_{21} and S_{12} phases, c) Group delay, d) Wideband S_{21} measurement.

Conclusion

In this project, we use new electromagnetic coupling for designing a new SIR structure and band-pass filter for an altimeter system to cancel jamming and noise. Frequency tuning, tolerating high power, low insertion loss, sharpness of the filter frequency response and wide stop-band make the filter very suitable for any wireless communication system. The filter has more than 80 dB rejection in stopband and less than 0.7 dB loss in passband and also the rejection band is at minimum up to 13 GHz and the rejection value is more than 80 dB. The final tests of altimeter show that the sensitivity of the receiver is more than -124 dB and we can achieve the maximum sensitivity of -130 dB. The EM simulation has confirmed the theory and measured results.

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