

# **Study of Rectangular Spiral Resonators and their Applications in MICS Band Notch Filters**

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**ABSTRACT:** The paper presents a comparative study of rectangular spiral resonators and their behaviour in a coplanar waveguide and a microstrip transmission line structure. When coupled to a coplanar waveguide line they imitate a series connected parallel LC resonant circuit to introduce a notch band. When directly connected to a microstrip line they form a shunt connected series LC resonant circuit to produce the required notch band. The third attempt places the spiral resonator inside the microstrip transmission line. Filter structures are developed utilizing these behaviour and their characteristics are compared. Spiral resonators are tuned to the mid band frequency (403.5MHz) of the MICS band (402MHz-405MHz).

**KEYWORDS:** Equivalent circuit, Group delay, MICS band, Notch band, Rectangular spiral resonators, Surface current.

## **I. INTRODUCTION**

U.S. Federal Communications Commission (FCC) created a specification and set aside a communication spectrum for the communication needs of diagnostic and therapeutic medical implants and body-worn medical devices. This is termed as Medical Device Radio communications Service (Med Radio). Cardiac pacemakers, defibrillators neuromuscular stimulators, drug delivery systems etc. are included in this category of devices. As of February 2016, communications spectrum for these and other similar devices is set aside at various points in the 400MHz frequency band. Medical Implant Communication Service (MICS) created by FCC set aside the 402–405 MHz band and designated a low maximum transmit power, EIRP of 25  $\mu$ W, in order to reduce the risk of interfering with other users of the same band. A similar process was initiated by the ETSI (European Telecommunications Standards Institute) in Europe in July 2004, with both the FCC and ETSI considering the 401–402 and 405–406MHz ranges. The FCC expanded MedRadio's spectrum again in November 2011, adding 24 MHz in the 413–419MHz, 426–432MHz, 438–444MHz, and 451–457MHz ranges.

Professional wireless microphones transmit in locally vacant TV channels, primarily in the Ultra High Frequency (UHF) range (<600MHz). UHF RFID tags operate from 300MHz to 3GHz. Such devices used in hospitals and public places are not supposed to interfere with MICS devices. An electromagnetic interference (EMI) filter attenuates one or more specific frequencies in order to provide electromagnetic compatibility of an electronic device while in the presence of an electromagnetic emitter operating at the same frequencies. In this work, an EMI filter is developed which consists of spiral resonators tuned to the specific MICS band frequencies. The notch EMI filter [1] can effectively attenuate the electromagnetic field of a powerful low frequency emitter which may interfere with the operation of critical medical devices and wireless medical telemetry services.

**Characteristics Of Rectangular Spiral Resonators**

Spiral inductors can be modeled as a parallel LC circuit. Coupling to the transmission line is determined by the way it is placed in the circuit. The inductance value is determined by the length of the spiral (which in turn depends on the number of turns) and capacitance determined by the gap between the turns.

**Band Notch Filter with Spiral Resonator Coupled To CPW Transmission**

The filter consists of a coplanar waveguide transmission line [2-8], to which two spiral resonators are coupled to introduce the required notch band. The resonators are tuned to the mid frequency of the MICS band, 403MHz. Fig. 1(a) shows the layout of a filter with a single spiral resonator, capacitively coupled to the CPW transmission line. The response of the structure (Fig.1 (b)) shows a rejection in the specified band, but the rejection level is quite low (8dB). The flat group delay for the filter indicates distortion less transmission for all frequencies except at the notch frequency.

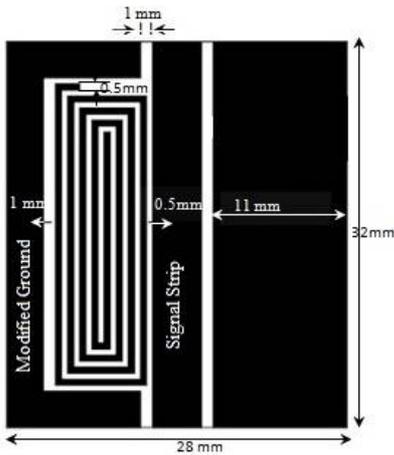


Fig. 1a Layout of the filter with One Spiral Resonator coupled to CPW transmission line

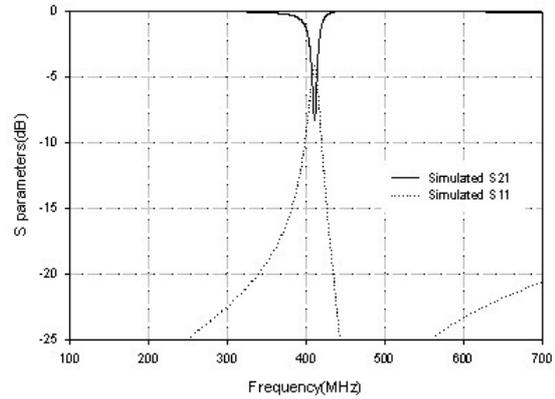


Fig. 1b Simulated S parameters

In order to improve rejection at the notch band, one more resonator is added on the other side. The final layout of the filter with two resonators is shown in Fig. 2(a) along with the improved S parameters [Fig. 2(b)]. The overall filter dimension is 28mm x 32mm.

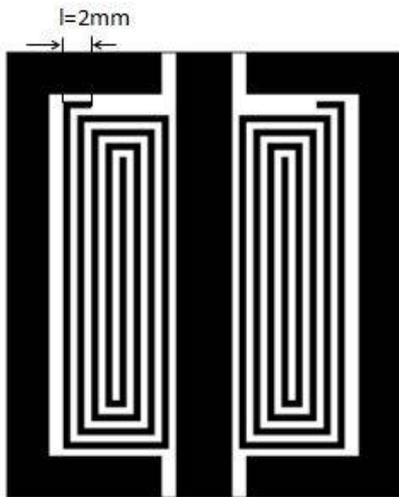


Fig. 2a Layout of the of the filter with two spiral resonators coupled to CPW transmission line

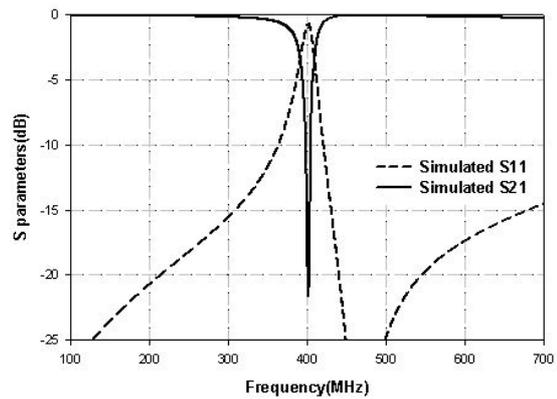


Fig. 2b Simulated S parameters of the filter

**Simulation Studies**

The surface current of the structure at the resonant frequency (403.5 MHz), as shown in Fig. 3(a) follows a counter clockwise distribution in one resonator and clockwise distribution in second resonator revealing the role of the spiral resonators in introducing the notch. Surface current at passband frequency (500MHz) is also plotted and shown in Fig. 3(b). Here the current flows through the edges of the resonator arms in opposite directions nullifying their effect. Thus the resonator remains inactive at passband frequencies. Fig. 4 shows the optimetric study on length (l) of the spiral inductor. The notch frequency increases on reducing the length of spiral inductor.

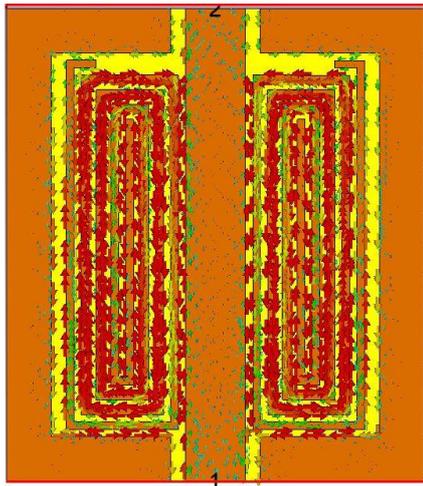


Fig. 3a Surface current vector at resonant frequency (403.5MHz)

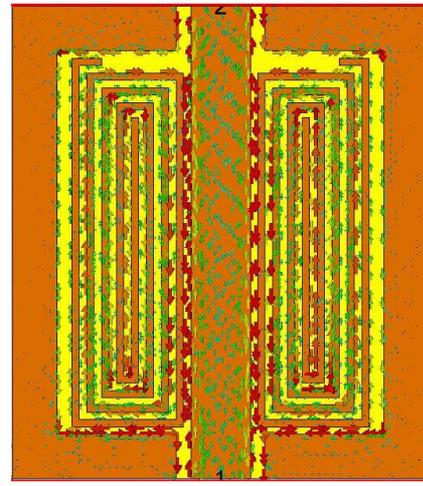


Fig. 3b Surface current vector at a passband frequency (500MHz)

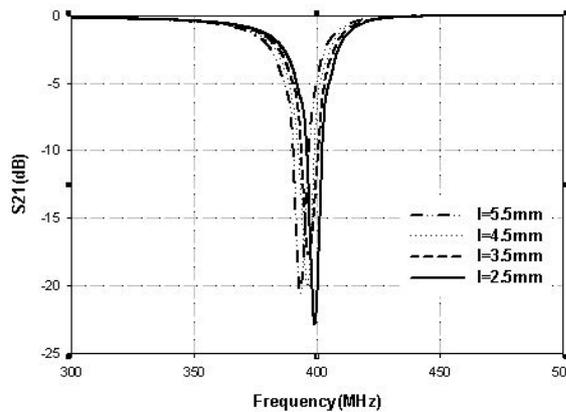


Fig. 4 Variation of notch frequency by changing the length( $l$ ) of the spiral inductor

The lumped element model extracted from  $S_{21}$  plot and its simulated  $S_{21}$  parameters are shown in Fig. 5(a-b).  $L_{sp}$  and  $C_{sp}$  represent the inductance and parasitic capacitance of spiral resonators;  $L_c$  and  $C_c$  represent the coplanar waveguide transmission line and  $L_m$ ,  $C_p$  the mutual coupling of the spiral inductors to the coplanar line.

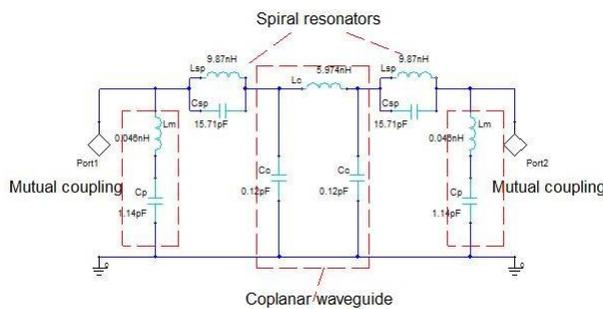


Fig. 5a. Lumped element model of the filter with two spiral resonators coupled to CPW transmission line

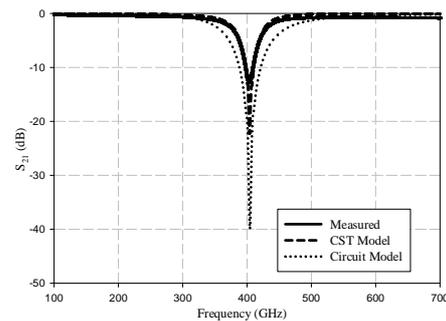


Fig. 5b. Comparison of Transmission Parameters of Circuit Model, CST Model and Prototype filter

**Experimental Results**

The filter structure is implemented on FR4-epoxy substrate with a dielectric constant of 4.4, thickness 1.6 mm and loss tangent 0.02. The photograph of the fabricated prototype filter is shown in Fig 6. Measurements are taken using Rohde and Schwarz ZVB 8 VNA. Experimental results closely agree with simulated results as shown in Fig. 7(a-c). Small discrepancies in the result can be attributed to the inaccuracies in the fabrication process. Group delay in Fig. 7c is almost flat in the passband and variation is less than 0.15ns. This reveals the linear phase nature of the filter, making it suitable for communication applications. The abrupt change in group delay at the notch frequency is due to the influence of the resonators. Table 1 summarizes the simulated and measured characteristics of the proposed filter.

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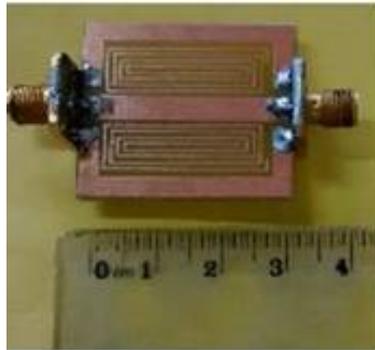


Fig. 6. Prototype filter with two spiral resonators coupled to CPW transmission line

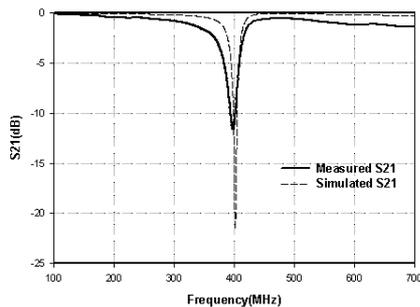


Fig. 7a.  $S_{21}$

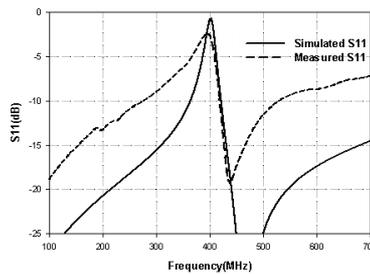


Fig. 7b.  $S_{11}$

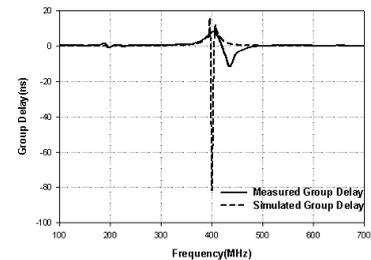


Fig. 7c Group Delay

Fig 7 Measured & simulated results of the filter with two spiral resonators coupled to CPW transmission line

Table 1 Performance of the notch filter with spiral inductors coupled to CPW line

Parameter	Simulation	Experiment
Resonant frequency	403.5MHz	400 MHz
Notch band	390MHz to 423MHz	370MHz to 423MHz
Notch depth	22dB (8dB with one resonator)	12dB

**Band Notch Filter with Spiral Resonator Stub on Microstrip Transmission Line**

The filter consists of single stub in the form of spiral resonator on a microstrip transmission line for introducing the required notch band. The resonator is tuned to the mid frequency of the MICS band, 403.5MHz. The layout of the filter is shown in Fig. 8(a) along with the S parameters (Fig. 8(b)).

The flat group delay for the filter indicates distortion less transmission for all frequencies except at the notch frequency. The notch band is from 378MHz to 423MHz with a notch depth of 16.27dB. The size of the filter structure is 15mm x 15.74mm.

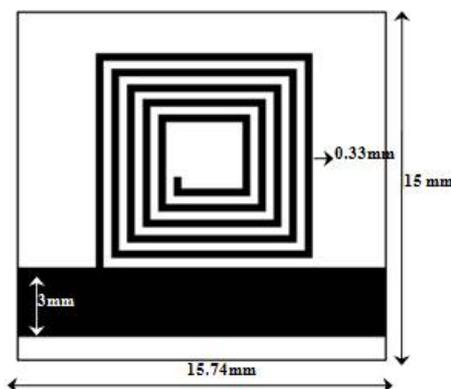


Fig 8a Layout of Filter with Spiral Resonator on Microstrip Transmission line

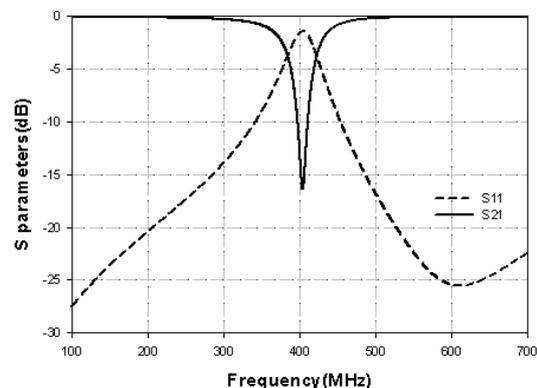


Fig 8b Simulated S parameters of Filter

**Simulation Studies**

The surface current of the structure at the resonant frequency is shown in Fig. 9(a). It shows that the spiral resonator is excited at the resonant frequency. Surface current at passband frequency (500MHz) plotted in Fig. 9(b) shows a good coupling between port1 and port2 at passband frequency.

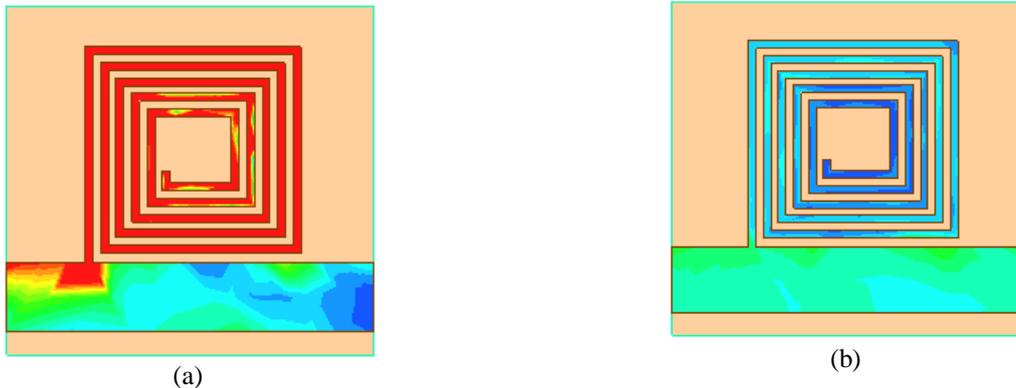


Fig 9(a) The surface current distribution of the filter with Spiral Resonator on Microstrip Transmission at the resonant frequency (403MHz) (b) Surface current at passband frequency (500MHz)

The lumped element model extracted from  $S_{21}$  plot and its simulated  $S_{21}$  parameters are shown in Fig. 10(a-b).  $L_{sp}$  and  $C_{sp}$  represent the inductance and capacitance of the spiral resonator stub.  $C_1$  is the coupling capacitance to the transmission line and distributed shunt capacitance shown as  $C_{sh}$ .

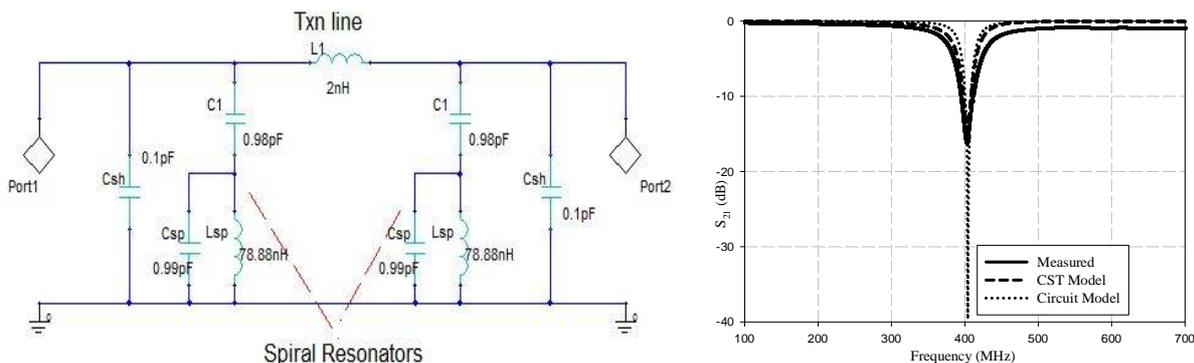


Fig.10 (a) Lumped element model of the filter with spiral resonator stub and (b) Comparison of Transmission Parameters of Circuit Model , CST Model and Prototype filter

**Experimental Results**

The filter structure is implemented on FR4-epoxy substrate with a dielectric constant of 4.4, thickness 1.6 mm and loss tangent 0.02. The photograph of the fabricated prototype filter is shown in Fig. 11. Measurements are taken using Rohde & Schwarz ZVB 8 VNA. Experimental results closely agree with simulated results as shown in Fig. 12(a-c). The notch band is from 377.34MHz to 429.64MHz with a notch depth of 16.2dB. Table 2 summarizes the simulated and measured characteristics of the proposed filter.



Fig 11. Photograph of Fabricated filter with Spiral Resonator Stub on Microstrip Transmission line.

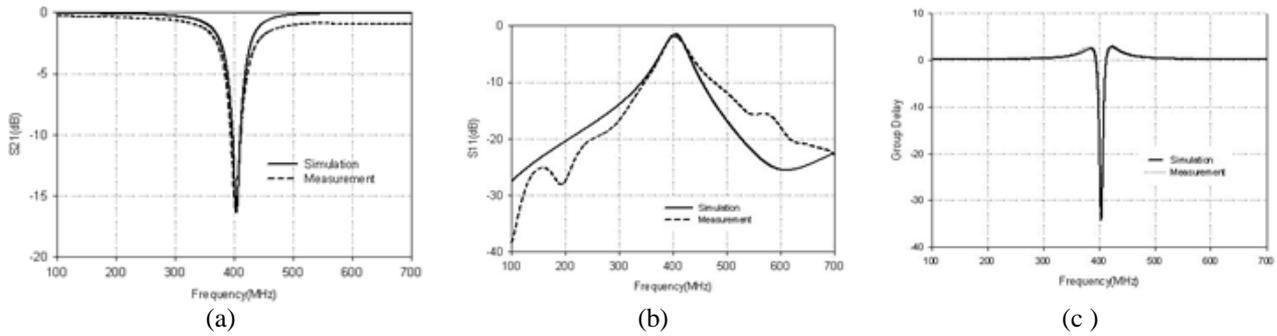


Fig. 12 Measured & Measured & Simulated results of the proposed filter with spiral resonator stub (a)  $S_{21}$  (b)  $S_{11}$  (c) Group Delay

Table 2 Performance of the notch filter with spiral resonator stub on microstrip line

Parameter	Simulation	Experiment
Resonant frequency	403.5MHz	403.5MHz
Notch band	378MHz to 423MHz	377.34MHz to 429.64MHz
Notch depth	16.27dB	16.2dB

**Band Notch Filter with Spiral Resonator Embedded In Microstrip Transmission Line**

The filter consists of a compact microstrip based spiral resonator embedded into a Microstrip Transmission line. The resonator is tuned to the mid frequency of the MICS band, 403.5MHz. The layout of the filter is shown in Fig. 13(a) along with the S parameters (Fig. 13(b)). The notch band is from 388MHz to 418MHz with a notch depth of 14.58dB. The size of the filter structure is 22mm x 9mm.

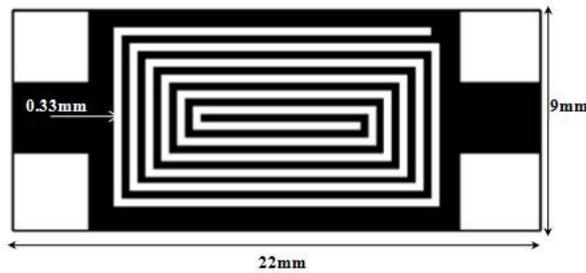


Fig 13(a) Layout of filter with Spiral Resonator embedded in Microstrip Transmission line

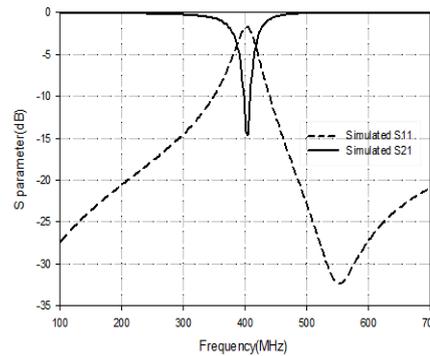


Fig 13(b) Simulated S parameters of filter

**Simulation Studies**

The surface current of the structure at the resonant frequency is shown in Fig. 14(a). It shows that the spiral resonator is excited at the resonant frequency. Surface current at passband frequency (500MHz) plotted in Fig. 14(b) shows good coupling between port1 and port2 at passband frequency.

The lumped element model extracted from  $S_{21}$  plot and its simulated  $S_{21}$  parameters are shown in Fig. 15(a-b).  $L_{sp}$  and  $C_{sp}$  represent the inductance and capacitance of the spiral resonator stub.  $L_1$  is the inductance of the transmission line and distributed shunt capacitance shown as  $C_{sh}$ .



Fig 14(a) The surface current distribution of the structure at the resonant frequency (403MHz) (b) Surface current at passband frequency (500MHz)

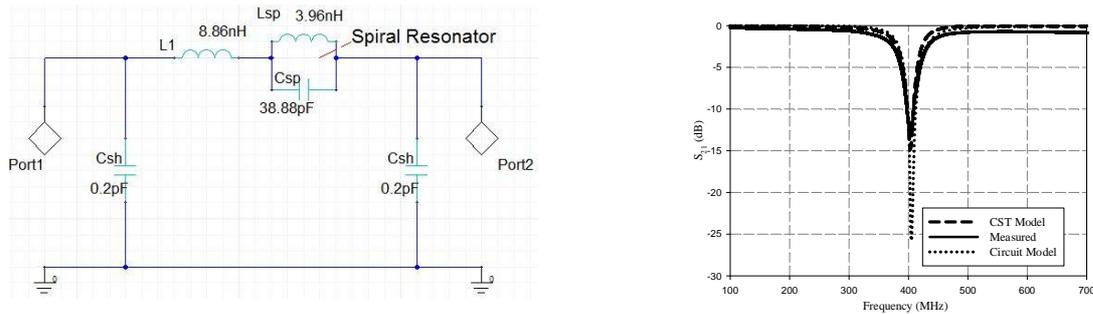


Fig.15 (a) Lumped element model of the filter with spiral resonator embedded in transmission line (b) Comparison of Transmission Parameters of Circuit Model , CST Model and Prototyped filter

**Experimental Results**

The filter structure is implemented on FR4-epoxy substrate with a dielectric constant of 4.4, thickness 1.6 mm and loss tangent 0.02. The photograph of the fabricated prototype filter is shown in Fig. 16.

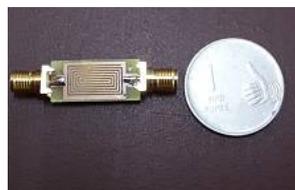


Fig 16. Photograph of Fabricated filter with Spiral Resonator embedded in Microstrip Transmission line.

Measurements are taken using Rohde & Schwarz ZVB 8 VNA. Experimental results closely agree with simulated results as shown in Fig. 17(a-c). The notch band is from 377.34MHz to 429.64MHz with a notch depth of 12.58dB. Table 3 summarizes the simulated and measured characteristics of the proposed filter.

Table 3 Performance of the filter with spiral resonator embedded in microstrip line

Parameter	Simulation	Experiment
Resonant frequency	403.5MHz	403.5MHz
Notch band	378MHz to 423MHz	368 MHz to 434 MHz
Notch depth	16.27dB	12.95dB

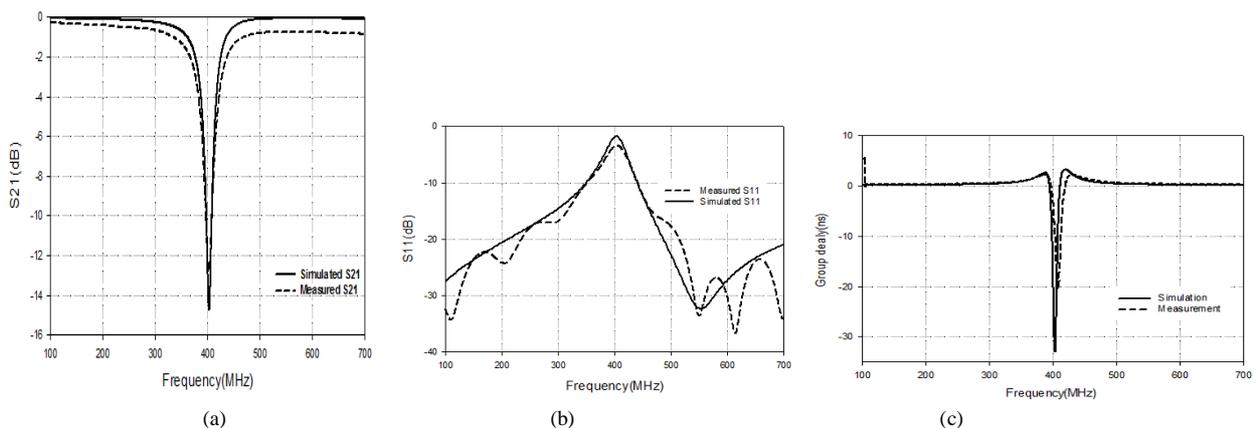


Fig. 17 Measured & Simulated Characteristics of proposed filter (a)  $S_{21}$  (b)  $S_{11}$  (c) Group Delay

**II.CONCLUSION**

The paper presents the different methods of coupling spiral resonators in both coplanar and microstrip transmission lines to produce a notch band. Table 4 shows the comparative study of parameters of the proposed filters. Amount of coupling offered varies in the three implementations as revealed by the transmission characteristics of the three filters

In spiral resonators coupled to CPW line, the rejection at notch band is 8dB with a single resonator and 22dB with two resonators. Higher rejection is obtained when spiral resonator stub is on the microstrip transmission line. The amount of rejection can be increased further at the cost of increased real estate. The study can be used as a guideline for implementing different filter structures according to the application requirement and ease of integration. This can be scaled to required bands of interest also.

Table 4 Comparative study of parameters of the proposed filters

Parameter	CPW coupled resonator filter	Filter with spiral Resonator Stub	Filter with embedded spiral resonator
Resonant frequency	403MHz	403.5 MHz	403.5 MHz
Notch band	390MHz to 410MHz	378 MHz to 423 MHz	368 MHz to 434 MHz
Notch depth	22 dB (8dB with single resonator)	16.27dB	12.95dB
Size	28mm x 32mm	15mm x 15.74mm	22mm x 9mm

### III.ACKNOWLEDGEMENTS

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