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Simulation Based Comparative Analysis of Resonant Frequency for Tunable Split Ring Resonator in Different Configurations

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Abstract*—Split ring resonators (SRR) are being researched for material sensing applications recently. These structures are easily fabricated and offer moderate quality factor (Q) and resonant frequencies (f_r). These structures provide limited tunability of f_r although considerable variation in Q has been established. A simulation based analysis has been carried out to find most appropriate and practical configuration of SSRs to provide considerable shift in f_r. Simulation results show efficacy of vertically stacked SRR vis-à-vis others configurations to achieve tunability.

***Keywords*—split ring resonator, tunability, vertically stacked split rings, complimentary split rings.**

I. Introduction

SSRs in various configurations have become an important component for design at microwave frequencies. These components provide low phase noise, moderate quality factor and ease of fabrication, even at minute scales. Recent advances in thin films processing have materialized these devices at nanometer levels. As size of split ring (SR) based resonant devices is very small as compared to the incident electromagnetic radiation, their use in development of meta-materials for terahertz frequencies have also been reported [1].

SR based resonator designs are being researched for fluid sensing and compositional analysis [2], [3] including biomedical sensors [4]. These designs primarily employ cavity perturbation methods to sense shift in f_r and change in Q when small amount of homogeneous solution of liquids is placed between the capacitive gap/split. These two parameters depend upon the dielectric constant of the resonator [5].

In this paper, a simulation based analysis of various design parameters is presented to find a most suitable and practically viable option for realization of tunable SSR. Tunable SSRs also form one of the basic configurations of unit cells for meta-materials.

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II. Theory

SSR can be modeled using *LC* network; inductive component comprises of length of wire which make the ring a single turn inductor. Gap/split faces and surface of the ring contribute to the total capacitance of SR [6]. Magnetic field surrounds the SR loop whereas conduction current and displacement current flows in circumferential direction on surface of loop and gap respectively [7]. The f_r of a SSR is given as

$$\mathrm{f_r} = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where *L* is the overall inductance of SR and *C* is the overall capacitance. Current flows on the inner wall of cavity and inner surface of SR due to skin depth [8] of material. A simple SSR is shown in Figure 1. A detailed simulation based comparative analysis of various SSR configurations has been evaluated [9]; inferring that each configuration needs its own set of mathematical equations to calculate the f_r. f_r of a cylindrical cavity can be easily controlled by the perturbation method mainly by area perturbation or cavity perturbation [10], [11].

SSRs can be divided into two broad categories; resonators employing single SR and resonators employing multiple SRs. This paper focuses on configurations based on single and two circular split rings placed inside a cylindrical cavity.

For a single SR based resonator, f_r predominantly depends upon the radius of the SR [12]. Design equation were developed by Rowe, David J., et al. for f_r and Q as a function of SR radius by curve fitting of simulated data

$$f_r = 0.0168r^2 - 0.502r + 5.19 \quad (2)$$

$$Q = -8.8r^2 + 78r + 1810 \quad (3)$$

where *r* is the radius of split ring.

Another method to control the f_r by broadside coupling has been demonstrate [13] with small variation of vertical gap (levitation) between two SR. A large number of configurations of stacked SRs have been simulated and discussed in this paper. These variations have also been discussed from the point of view of ease of fabrication and practical implementation.

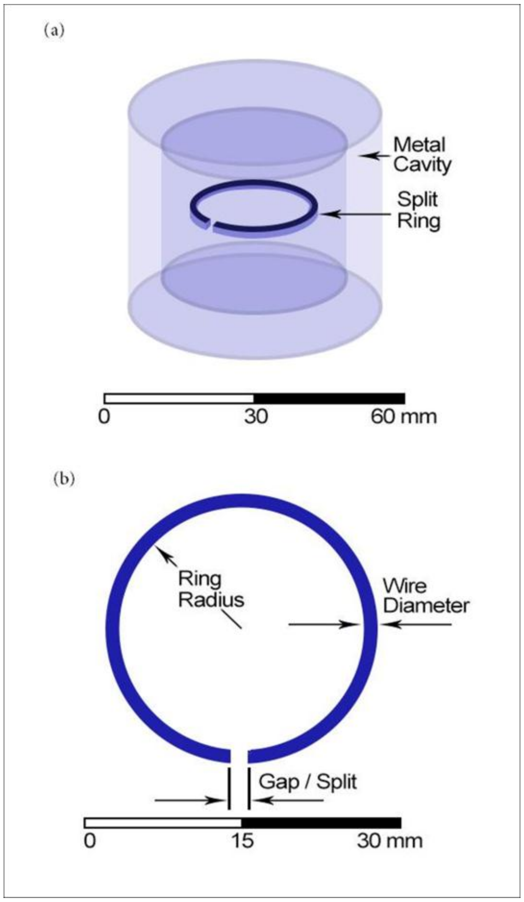

Figure 1 - Design structure for single SSR a) SSR within metallic cylindrical cavity (b) SR showing the gap/ split

III. Design Structure and Simulation

ANSYS HFSS© (version 13.0) [14] has been used for design of 3-D models and simulation of various configurations of SSRs. These simulations have been grouped in three major categories;

Group-I Cavity with single SSR

Group-II Cavity with two vertically stacked SSRs (of same dimensions)

Group-III Cavity with complementary SRs (SRs residing within each other)

The dimensions of metallic cylindrical cavity and other optimized parameters [9], [15], [5] used for simulations are shown in Table 1. The material selected for cavity and SRs are Aluminum and Copper respectively [17]. The design structure of single SSR is shown in Figure 1.

Group–I: Cavity with single SSR. Most basic and simple design involves single SR placed inside a metallic cavity as shown in Figure 1(a). This configuration has widely been used for material sensing experiments. Simulation results for f_r for

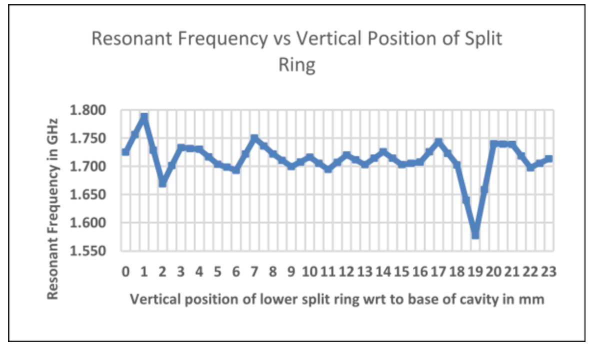

Figure 2a - Resonant frequency of single SSR with variation of vertical position of SR along cavity axis

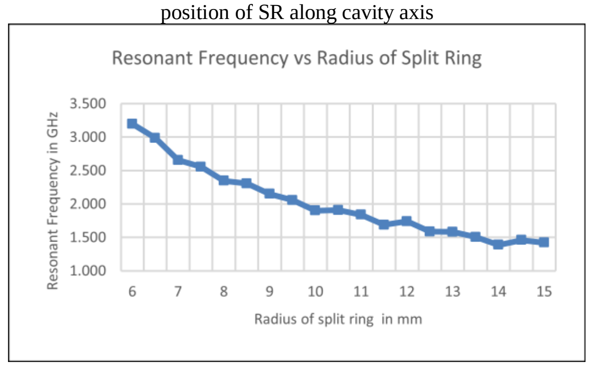

Figure 2b – Shift in resonant Frequency with variation in radius of SR

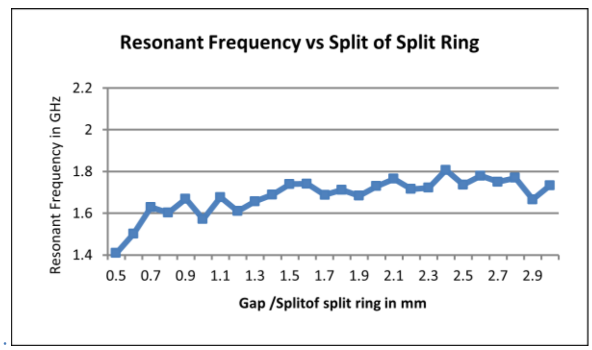

Figure 2c – Shift in resonant Frequency with variation in capacitive gap / split of SR

different vertical positions of SR relative to inner base of cavity are shown in Figure 2a.

TABLE – 1: OPTIMIZED DESIGN PARAMETERS

Parameter	Design value
Inner diameter of cavity	38 mm
Shield thickness of cavity	7 mm
Height of cavity	30 mm
Capacitive gap (split) or ring	1.5 mm
Dimension of ring wire	1mmx1mm
Geometry of ring wire	Square
Material of cavity	Aluminum
Material of rings	Copper
Space inside cavity	Air

Simulated results confirm shift in f_r with change in SR radius [12], as dependence of f_r on radius has been linked by Equations (2) and (3). It provides optimum radii of the SR to achieve maximum shift in f_r. 6 – 9 mm radii exhibit maximum

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shift. The f_r for various values of SR radii are plotted in Figure 2b.

Surface and gap capacitance of gap / split can also result in shift in f_r. Figure 2c shows the f_r response for gradual variation of capacitive gap from 0.5 mm to 3 mm.

Group – II: Cavity with two vertically stacked SSRs. This configuration comprises of two vertically stacked split rings (VS-SR) with gap between them. Lower SR is fixed (static) whereas upper ring is moved upward along the cavity axis thus increasing the gap between two rings. A pneumatic or air assisted mechanism has been demonstrated to achieve levitation of upper ring up to 0.2 mm [13]. Splits of both the resonators are 180^{o} out of phase to achieve maximum coupling. Shift in f_r is realized by variation of vertical gap between the lower and upper SR. This configuration of SR is shown in Figure-3c.

The vertical gap between the SR was varied from 1 to 10 mm gradually for two scenarios; lower ring placed 1 mm above base of cavity and lower ring placed 10 mm above base of cavity. Simulated results for f_r for both the cases are plotted in Figure 3a and b respectively. Former scenario shows ~ 0.5 GHz shift in f_r with gradual increase in vertical gap between the SR s.

Group – III: Cavity with Complementary SRs (residing within each other). Complementary SRs (one SR is placed inside another SR in the same plane) is another configuration which can provide significant shift in f_r; when position of one ring is varied with respect to other. Structural dimensions of complementary SRs for this configuration are listed in Table 2 and shown in Figure 3d. The radii of SRs are selected to be between 6-9 mm as this range of radii has shown maximum shift in f_r during simulation of Group-I configurations. Four design variations were simulated for complementary SRs to investigate shift in f_r.

TABLE – 2: DIMENSION OF COMPLEMENTARY SRS

Parameter	Design value
Radius of outer SR	8 mm
Radius of outer SR	6 mm
Capacitive gap (split) or ring	1.5 mm
Dimension of ring wire	1mmx1mm
Geometry of ring wire	Square
Material of cavity	Aluminum
Material of rings	Copper
Space inside cavity	Air

Option-1: Inner SR is placed fixed 1 mm above base of cavity and outer ring is gradually moved upward. The dimensions of ring wire are same for the inner and outer SRs.

Option-2: Outer SR is placed fixed 1 mm above base of cavity and inner ring is gradually moved upward.

Option-3: Height of inner SR is increased to 10 mm forming a split cylinder. Split cylinder is placed 1 mm above base of cavity. Outer SR dimensions are maintained as per Table 2 and gradually moved upward.

Option-4: In this case height of outer SR is increased to 10 mm. Both the rings are placed 1 mm above base of cavity as initial position. Dimensions of inner SR are kept as per

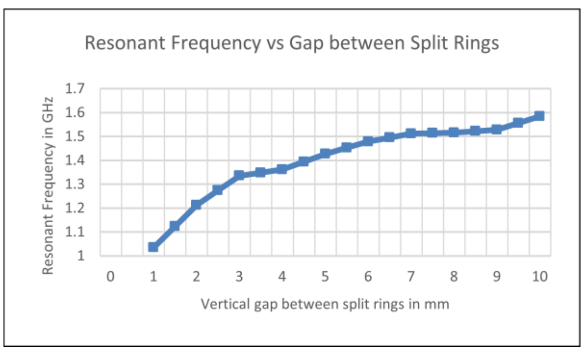

Figure 3a. Lower SR placed 10 mm above the base of cavity (one third of cavity height) and gap varied from 1 mm to 10 mm

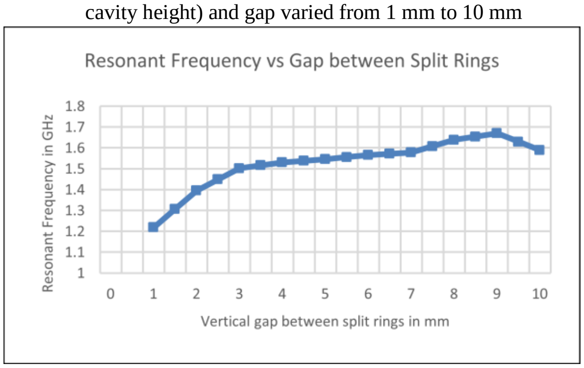

Figure 3b. Lower SR placed 1 mm above the base of cavity and gap varied from 1 mm to 10 mm

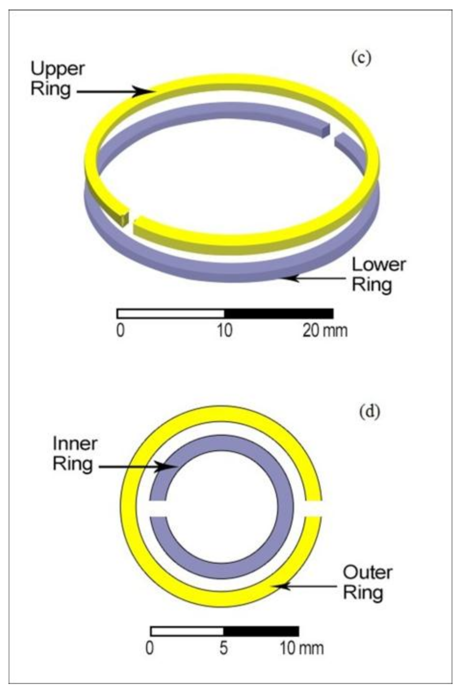

Figure 3 (c) HFSS 3-D model of VS-SR for Group-II configuration
(d) complementary SSRs for Group-III configuration

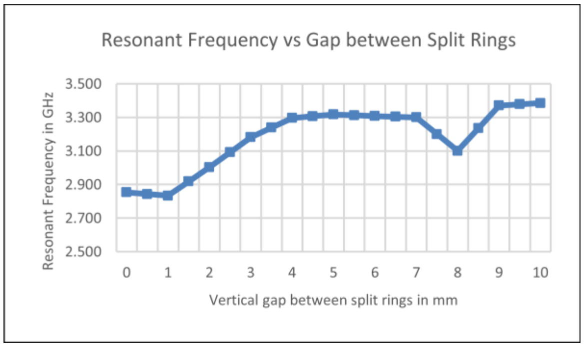

Figure 4a - Inner ring is moved upward in the cavity whereas outer ring is placed at 1 mm above base of cavity.

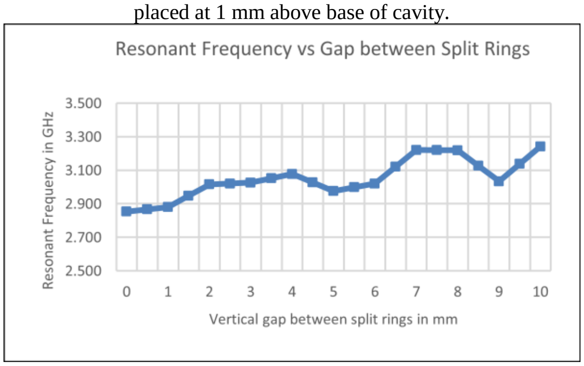

Figure 4b - Outer ring is moved upward in the cavity whereas inner ring is placed at 1 mm above base of cavity.

Table 2. Inner SR is gradually moved upward.

Simulated results of these design variations are plotted in Figures 4a-c.

IV. Analysis and Discussion

Data of results of three configurations of SRs have been analyzed and discussed with a focus on extent of shift in f_r achieved.

Group-I. Change in vertical position of SR inside cavity is the most simple and easy to implement. However, tunability over a considerable broad range could not be achieved. Inner surface areas of cavity and SR remained unchanged in this configuration which can be attributed to a mostly stable f_r response.

A huge shift in frequency was observed when radius of SR was varied. Change in radius changed the surface area of SR. This option provides maximum shift in f_r for tunability of resonator but it is not practical to change the radius of metallic ring within the cavity. However, this analysis provides an insight to the range of radii of SR which provide maximum shift in f_r.

Change in gap /split of ring has also been investigated. Very small shift in f_r was observed. This can be attributed to presence of surface capacitance of ring which does not change significantly. Overall capacitance of SR is combination of surface capacitance and gap capacitance. Gap capacitance dominates at narrow gaps only [6].

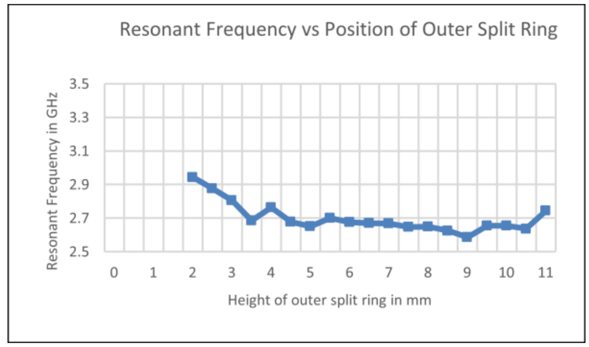

Figure 4c - Height of inner SR is fixed at 10 mm and outer split ring is moved up from lower position.

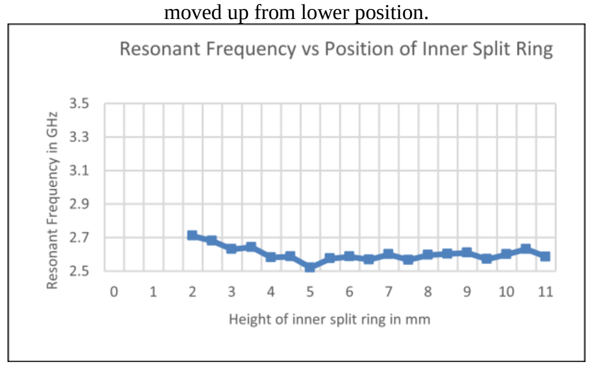

Figure 4d - Height of outer split ring is fixed at 10 mm and inner split ring is moved up from lower position.

Group-II. In case of VS-SRs configuration, considerable shift in f_r is achieved in both the simulated configurations. This shift in f_r can be attributed to change in the broad side coupling of two SRs as gap between SRs is varied. Increase in vertical gap between the rings reduces the broad side coupling and hence results in shift in f_r. SRs placed at the bottom of the cavity provide better shift in f_r.

Both the options in this configuration are easy to manufacture and implement. A mechanism can be introduced to move the upper SR to achieve tunable SSR.

Group-III. Various configurations of complementary SRs have also provided shift in f_r. Figure 4 shows that this phenomenon is generally less pronounced and maximum shift achieved is also less as compared to Group-II configurations. Furthermore, large variations in adjacent values make it less suitable for tunability. Options 1, 3 and 4 exhibit small shifts in resonant frequency as compared to Option 2.

Comparison of Group I, II and III Configurations.

Results of HFSS simulations are combined and tabulated in Table 3 and graphically represented in Figure 5. Horizontal axis in Figure 5 represents vertical position of SR and radius of SR in mm for Group-I (2a and 2b), gap between the SRs in mm for Group-II (3a and 3b) and vertical position of inner and outer SRs with respect to base of cavity for Group-III (4a to 4d) simulations.

Group II configurations are most suitable and practical to achieve considerable shift in f_r. These configurations provide 0.549 GHz and 0.451 GHz shift in f_r over 10 mm displacement of upper SR. Practical configurations in Group I

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and Group III provide very less shift in f_r as compared to Group II.

Figure 5 sums up the results of all configurations simulated. It is pertinent to notice that for large vertical gap between the SRs for Group II (Group-II inset), the values of f_r approach the values for Group I with single SR. This shows that the coupling between the two rings at these values of vertical gap has weakened significantly. Group II configurations show smooth shift as compared to Group III (Group III inset) configurations. This furthers strengthens findings that Group II configurations are best suited toward achieving tunable SSR.

V. Conclusion

In this paper, a comprehensive simulation based comparative analysis of different configurations of SRs is presented to achieve a considerable shift in resonant frequency (f_r) aimed at realization of a tunable SSR. Three models have been developed, simulated and analyzed. Best practical option to achieve shift in f_r with variation of vertical gap between SRs in VS-SRs configuration. Simulations show smooth and considerable shift in f_r. It is almost impractical to achieve considerable shift in f_r with single SSR.

Practical implementation of this configuration for tunable resonators can be used in development of metamaterials. Quality factor (Q) of a resonator is another important performance parameter which needs to be investigated to find a solution with better selectivity of resonators.

TABLE – 3: MINIMUM AND MAXIMUM f_r FOR DIFFERENT CONFIGURATIONS OF SSRS

Model		f_r (GHz) Min	f_r (GHz) Max	Max Shift (GHz)	Practical Implementation
Group-1	Change of vertical position of SR from 1 mm to 25 mm (Fig 2a)	1.577	1.788	0.211	Yes
	Change of radius of SR from 6mm to 15 mm (Fig 2b)	1.421	3.196	1.775	No
Group-2	Lower SR placed 10 mm above the base of cavity and gap varied from 1mm to 10 mm (Fig 3a)	1.585	1.035	0.549	Yes
	Lower SR placed 1 mm above the base of cavity and gap varied from 1mm to 10 mm (Fig 3b)	1.670	1.219	0.451	Yes
Group-3	Inner ring is moved upward in the cavity whereas outer ring is placed at 1 mm above base of cavity (Fig 4a)	2.585	2.710	0.125	Yes
	Outer ring is moved upward in the cavity whereas inner ring is placed at 1 mm above base of cavity (Fig 4b)	2.853	3.242	0.389	Yes
	Height of inner ring is fixed at 10 mm and outer split ring is moved up from lower position (Fig 4c)	2.745	2.944	0.199	Yes
	Height of outer ring is fixed at 10 mm and inner split ring is moved up from lower position (Fig 4d)	2.585	2.710	0.125	Yes

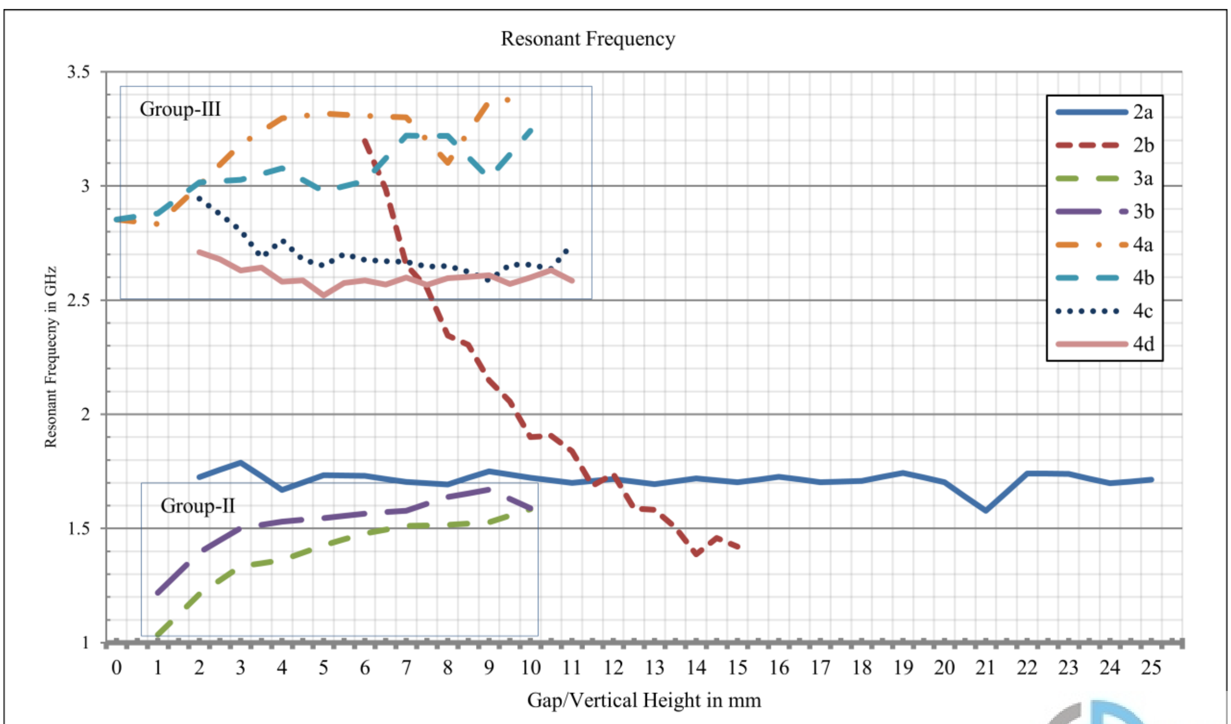

Figure 5 – Resonant frequencies for various configurations of SRs combined.

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