Chapter Six

SRR BASED WAVEGUIDE FILTER

This chapter presents the behavior of SRR in waveguide for the development of bandstop and bandpass filters. Use of SRR array for the rejection of a desired band above the cut-off frequency of the waveguide is investigated in the beginning of the chapter. Also, the frequency response of the waveguide below cut-off with SRR insert is explored for the development of bandpass filter. This study leads to the phenomenon of waveguide miniaturization.
6.1 Introduction

The classical rectangular waveguide theory is still very much usable in order to build various filter structures, which can meet requirements of the modern technology. The ability of SRRs to inhibit signal propagation in the vicinity of the resonant frequency when properly excited (magnetic field normal to its plane), have already been utilized for the development of several planar filters.

An array of SRR, when placed along the center of the waveguide with the magnetic field parallel to the SRR axis, inhibits the propagation of signal from input port to the output port at the resonant frequency above the waveguide cut off. The same structure can also be used for passing a desired frequency band below the waveguide cut off, in the vicinity of its resonant frequency pointing towards the miniaturization of the waveguide filter. A detailed investigation on the bandwidth characteristics of both stopband and passband with the parameters of the array within the waveguide are carried out. The simulation carried out using Ansoft HFSS has been validated by fabrication and measurement.

- Transmission properties of SRR in a waveguide

In this section, the propagation characteristics of a waveguide with array of SRR placed along the axis is discussed. A narrow band rejection is obtained at the first resonant frequency of the SRR, whereas a wide band rejection is obtained at the second resonance.

Rectangular waveguides were one of the earliest types of transmission lines used to transport high frequency signals and are still used today for many high power and low loss systems at microwave and mm wave frequencies. The hollow rectangular waveguide can propagate TE and TM modes, but not TEM waves. Figure 6.1 shows a rectangular waveguide with dimension a and b and parameters \( \varepsilon \) and \( \mu \).
The cut-off frequency is given by,

$$f_c = \frac{1}{2\sqrt{\varepsilon\mu}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2} \text{ Hz} \quad (6.1)$$

where, $m$ and $n$ represent possible modes in $x$ and $y$ directions.

For dominant mode $TE_{10}$,

$$f_c = \frac{1}{2a\sqrt{\varepsilon\mu}} \text{ Hz} \quad (6.2)$$

SRR array is placed along the center of the waveguide as shown in Fig. 6.2 since the electric field intensity is highest at center of the waveguide, making it possible to achieve greatest interaction of the SRR array with the electric field. Also, as already mentioned, the SRR would be excited by a time varying magnetic field with significant component parallel to the ring axis.
Fig. 6.2 SRR array loaded rectangular waveguide

From basic electromagnetic (Balanis, 1989), it is known that one can resolve fields of the TE waveguide mode into two plane waves (Fig. 6.3(a)). These plane waves propagate along the waveguide in the zigzag fashion due to successive reflections at waveguide walls.

Fig. 6.3 Propagation in the waveguide filled with SRR array (a) The equivalent plane wave (b) The propagation in the transversal direction (c) The propagation in the longitudinal direction.
For each plane wave, the longitudinal components of the magnetic field vector $H_I$ and the electric field vector $E$ define the transversal component of the Poynting vector $P_t$ (Fig. 6.3(b)). This component of Poynting vector experiences total reflection at the waveguide walls. It causes standing wave in the transversal direction, the existence of which is needed in order to satisfy the boundary conditions. The transverse component of the magnetic field $H_t$ and $E$ produces a Poynting vector in the axial direction as shown in Fig.6.3(c).

The SRR can be thought of as a small capacitively loaded loop antenna (Harbar et al., 2005). The current flowing through the loop antenna (SRR) is induced by the component of the magnetic field vector that is perpendicular to the loop. Hence, it is the transversal component of the magnetic field ($H_t$), which is perpendicular to the SRR which will give rise to the induced current causing the resonance.

### 6.1.1 Bandstop characteristics of SRR in waveguide

In this section the band rejection behavior of the SRR array centrally placed in an S-band waveguide is investigated. The SRR unit cell is designed to operate at 3.7 GHz lying in the S-band spectrum. An array of ten SRR unit cells is placed along the axis of the S-band waveguide, which is excited in the $TE_{10}$ mode with two coaxial-to-rectangular waveguide transitions as input and output. The arrangement of SRR array inside the waveguide and its transmission characteristics are illustrated in the Fig.6.4 (a&b) respectively.

The simulation studies using Ansoft HFSS™ showed absorption dips at the designed resonant frequency and at higher resonance. The first resonance is in the S-band while the second resonance in the X-band region.
Fig. 6.4 (a) SRR array loaded S-band waveguide (p=10mm, N=10, r₁=1.6mm, r₂=2.7mm, d=0.2mm, c=0.9mm, s=0.5mm) (b) Transmission characteristics

Since the dimension of the SRR unit cell is very small compared to the waveguide height, very few magnetic field lines penetrate through the SRR to produce considerable attenuation. The level of attenuation and bandwidth can be improved by increasing the number of SRRs along the y axis in the array so that maximum H-field lines penetrate the SRR cells.

Fig. 6.5 (a) Three rows of SRR array loaded S-band waveguide of SRRs (b) Transmission characteristics
Chapter 6

The transmission characteristics in Fig.6.5 shows considerable attenuation at the resonant frequency with improved bandwidth, but with increased passband insertion loss which is due to the coupling between the closely placed resonator elements.

Another technique to improve the stopband characteristics with minimum passband loss is by utilizing the second resonance of a larger SRR which lies in the S-band region. To attain this, an SRR array with 10 unit cells with larger dimension designed to generate the second resonance at 3.7GHz is inserted in the S-band waveguide (Fig. 6.6a).

![SRR array loaded S-band waveguide](image)

**Fig. 6.6(a)** SRR array loaded S-band waveguide (p=17.8mm, N=10, r1=5.5mm, r2=6.6mm, d=0.2mm, c=0.9mm, s=0.5mm) **(b)** Transmission characteristics of the S-band waveguide loaded with SRR array

The transmission characteristics in Fig.6.6 (b) shows a rejection band with minimum passband insertion loss. It is evident from the plot that the rejection characteristic is better than that shown in Fig.6.5 which is due to the enhanced interaction of the H fields with the larger SRR compared to the smaller one.

At higher frequencies, the dimension of SRR becomes extremely small causing fabrication limitations. In order to develop waveguide bandstop filter using SRR at
higher frequencies, SRR of dimension with its second harmonics, lying in the desired frequency region will be a good choice.

Figure 6.7(a) shows the schematic of the X-band waveguide with SRR array having the fundamental resonance at 3.7GHz and second resonance around 7.5GHz.

![Figure 6.7(a) The SRR array in X-band waveguide (r1=1.6mm, r2=2.7mm, d=0.2mm, c=0.9mm, s=0.5mm, p=10mm) (b) Enhanced Second resonance in the X-band waveguide](image)

Figure 6.7(b) shows significant attenuation with low passband insertion loss when the SRR array is centrally placed in the X-band waveguide, since the second resonance of the SRR lies in the X-band region where signal propagation is in the lowest TE mode of the X-band waveguide. Here, the diameter of the SRR is comparable to the waveguide height giving rise to good interaction of H field with the SRR array.

- **Effect of number of resonators**

For filter fabrication, the number of resonators for considerable attenuation is optimized by inserting the SRR array with varying number (N) of cells on a single-sided FR4 substrate of dielectric constant 4.4 and height 1.6mm, with a period of 10mm. An absorption dip is observed in the waveguide passband at around 7.8 GHz. The experiment is repeated using arrays with different number of unit cells. It is found that the attenuation is increasing with the number of...
unit cells, as shown in Fig. 6.8(a). With \( N = 12 \), the received power level reaches the noise floor of the measuring instrument.

Fig. 6.8 Measured S parameter of standard X-band waveguide filled with SRR array of varying number of unit cells\((r_1=1.6\text{mm}, r_2=2.7\text{mm}, d=0.2\text{mm}, c=0.9\text{mm}, s=0.5\text{mm})\)

- **Effect of position of the array inside the waveguide**

Now, the SRR array with optimum number of unit cells\((N=12)\) is moved along the broadside (x-axis) of the waveguide and the transmission characteristics are studied with the distance from the narrow wall. The transmission coefficient \( S_{21} \) obtained as the SRR array was moved towards the waveguide wall is given in Fig. 6.9(a).

![Fig. 6.8](image)

**Fig. 6.9** (a) Bandwidth variation with position (b) Variation in bandwidth vs. position of the SRR array
The width of the stopband varies with the distance $x$ of the SRR array along the $x$-direction. At the center line of the waveguide, i.e., at $x=11.5$mm, it was found that the array produces maximum attenuation since the $H$ field lines are exactly perpendicular to the plane containing SRR array producing maximum interaction. Here, $x = 0$ corresponds to the rings in contact with the narrow wall of the waveguide. The bandwidth variation with position of the array within the waveguide is shown in Fig. 6.9, where the bandwidth is narrow near the walls increasing to a maximum at the center. A -10dB absorption dip was observed in the waveguide passband from 7.25GHz, which extended up to 8.5GHz.

### 6.1.2 Bandpass characteristics of SRR in waveguide: Waveguide miniaturization

A disadvantage of using waveguide filters is the relatively large size required for low-frequency operation. Therefore, physical dimension of the waveguide is an important parameter that needs to be considered.

In this section, a Ku-band waveguide is loaded with periodically arranged SRRs along the waveguide line of symmetry. As discussed in the previous section the wide band nature and bandwidth tunability, with position inside the waveguide of second resonant band, is utilized to generate a wide passband with adjustable bandwidth in the X-band region using a Ku-band waveguide; thus attaining waveguide miniaturization.

A SRR array of 18 unit cells with a period $a=10$mm was fabricated on an FR4 substrate of $h=1.6$mm, loss tangent=0.02 and dielectric constant 4.4. The SRR array is inserted along the center of the Ku-band waveguide. The length of the inclusion was selected so as to extend till the waveguide adapter port (Fig.6.10) to enable the efficient coupling at the lower frequencies in the vicinity of the resonant frequency of the SRR. Here, inorder to obtain passband below waveguide cut off, SRR with resonant frequency below the waveguide cut off is selected.
Chapter 6

Fig. 6.10 SRR array inserted Ku-band waveguide

The structure is simulated using Ansoft HFSS and results are shown in Fig. 6.11. One can notice that the two propagation passbands appear below the waveguide cutoff, one at the fundamental frequency 3.6GHz and other at twice the fundamental resonance (7.0GHz).

Fig. 6.11 Simulated transmission coefficients of a Ku-waveguide with SRR array

A very narrow band was observed at the resonant frequency with a large insertion loss of about -42dB. Whereas a wider band was obtained at the second resonance with minimum losses. In order to verify the phenomenon of propagation below cutoff, a Ku-band waveguide has been inserted with an array of SRR containing 18 resonators as shown in the photograph of Fig. 6.12 (a). In order to allow maximum coupling, the SRR array was extended till the probes of waveguide adapters. The measurement was carried out in Agilent Network Analyzer HP8510C. The measured transmission coefficient ($S_{21}$) is shown in Fig. (6.12b). The experimental results show a
SRR based waveguide filter

single passband in the cutoff region at the second resonance. The band corresponding to the fundamental frequency is not visible due to large insertion loss.

Fig. 6.12(a) Photograph of the Ku-waveguide loaded with SRR array (b) measured transmission coefficient

The large insertion loss is due to the weak coupling of the frequencies below Ku-band cut-off. The wide passband in the X-band region using the Ku-band waveguide proves the role of SRR in miniaturization of waveguide.

6.2 Conclusion

It has been shown both theoretically and experimentally that rectangular waveguide filled with SRR array inhibits the propagation above the cut-off of the waveguide and supports propagation below the cut-off frequency. The attraction of this work is that instead of exploiting the fundamental resonant frequency of the SRR, the second harmonics is utilized to control the bandwidth of the two types of filters.

References
Chapter 6