PRINTED PERIODIC WAVEGUIDE STRUCTURES: Full-wave characterization, Guided-wave characteristics and Applications

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Presentation in a Nutshell

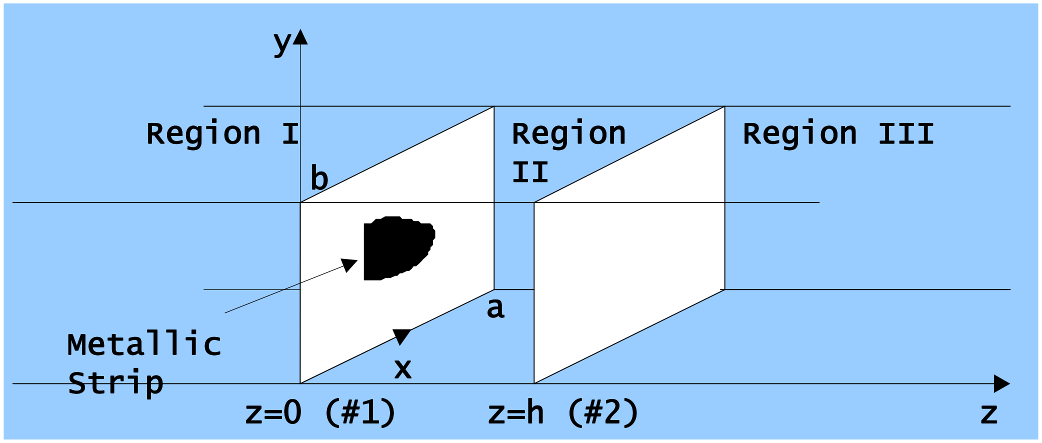
1. Full-wave characterization
   - Impedance-type Hybrid MoM-Immittance Approach (HMIA) for printed strip
   - Equivalent circuit extraction
   - Efficiency comparison and experimental validation
2. Guided-wave characteristics
   - Per-unit length transmission parameters
   - Frequency Selective Surface (FSS) strip printed periodic waveguide
   - FSS slot printed periodic waveguide
3. Applications
   - Novel Stepped Impedance Slot (SIS) resonator waveguide filters
   - Waveguide based EBG/PBG structures
   - Novel architecture for waveguide based DNG metamaterials

Section I

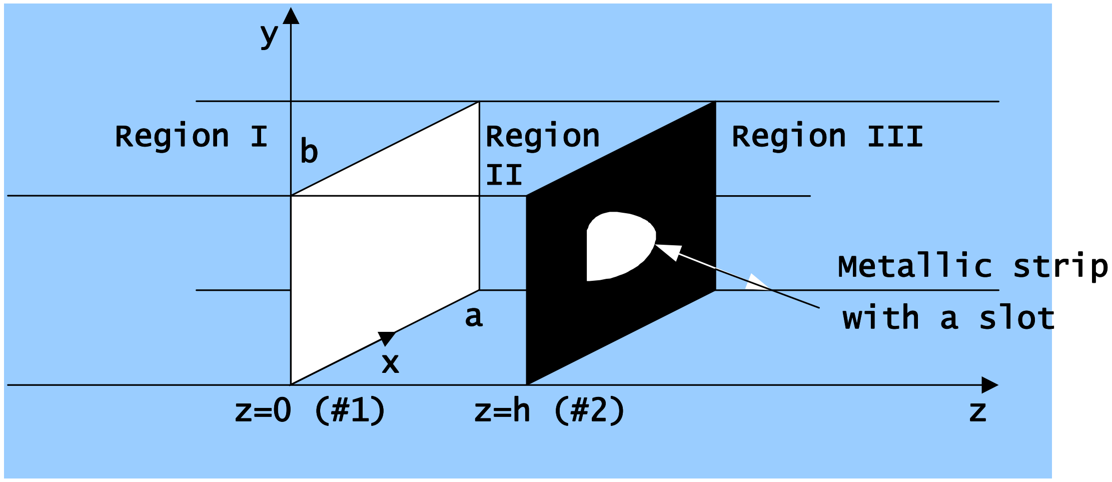
Full-wave Characterization[1]

1) R. S. Kshetrimayum and L. Zhu , "**Hybrid MOM-Immittance approach for full-wave characterization of printed strips and slots in layered waveguide and its applications,**" *IEICE Trans. On Electronics: Special Section on Measurement Technologies for Microwave Materials, Devices and Circuits*, Vol. E87-C, No. 5, pp. 700-707, May 2004.

Printed Strip and Slot



Printed strip



Printed slot

Steps in HMIA

Develop an integral equation from the boundary conditions of electric/magnetic field at interface

↓

Apply the Galerkin's method of Method-of-Moments (MoM) to the integral equation to get a matrix system of linear equations

↓

Solve the matrix system of linear equations to get the unknown current or voltage coefficients

↓

Get the scattering parameters and convert it to ABCD parameters then Z parameters to extract the equivalent circuit

Impedance-type HMIA for printed strip

1. Electric Field Integral Equation (EFIE)

- total tangential incident and scattered electric field at the interface is zero
- scattered electric field expressed in terms of electric dyadic Green's function and unknown electric current density on printed strip

$$\hat{z} \times (\overline{E}^{inc}(\overline{r}) + \overline{E}^{scatt}(\overline{r})) = 0$$

$$\hat{z} \times (\overline{E}^{inc}(\overline{r}) + \int_{strip} \overline{\overline{G}}_{EJ}(\overline{r}, \overline{r}').\overline{J}(\overline{r}')d\overline{S}') = 0$$

After applying Galerkin's method to the EFIE, we get a matrix system of linear equations.

Impedance-type HMIA for printed strip

2. Impedance-type HMIA Matrix

$$\begin{bmatrix}[Zxx] & [Zxy]\\ [Zyx] & [Zyy]\end{bmatrix}\begin{bmatrix}[Ix]\\ [Iy]\end{bmatrix} = \begin{bmatrix}[Vx]\\ [Vy]\end{bmatrix}$$

Voltage matrix

Impedance matrix

Current matrix

$$z_{xx}(m,n) = -\sum_{m=0}^{M+1}\sum_{n=0}^{N+1}\tilde{T}_x^*(k_{xm},k_{yn})\tilde{G}_{EJ}^{xx}(k_{xm},k_{yn})\tilde{B}_x(k_{xm},k_{yn})$$

$$z_{yx}(m,n) = -\sum_{m=0}^{M+1}\sum_{n=0}^{N+1}\tilde{T}_y^*(k_{xm},k_{yn})\tilde{G}_{EJ}^{yx}(k_{xm},k_{yn})\tilde{B}_x(k_{xm},k_{yn})$$

$$z_{yy}(m,n) = -\sum_{m=0}^{M+1}\sum_{n=0}^{N+1}\tilde{T}_y^*(k_{xm},k_{yn})\tilde{G}_{EJ}^{yy}(k_{xm},k_{yn})\tilde{B}_y(k_{xm},k_{yn})$$

Impedance-type HMIA for printed strip

$$v_x = \iint_{strip} T_x^*(x,y) E_x^{inc}(x,y) dxdy$$

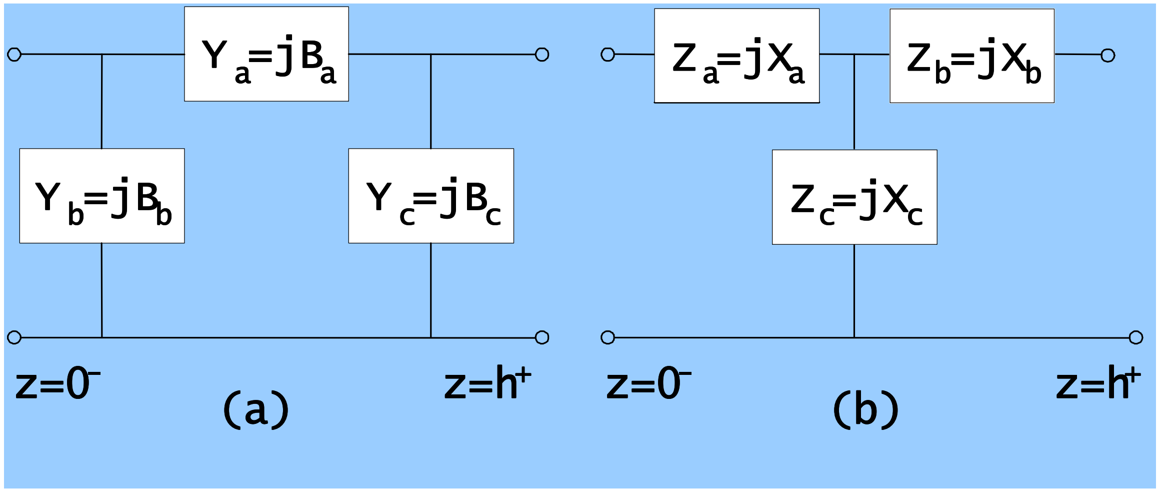
$$v_y = \iint_{strip} T_y^*(x,y) E_y^{inc}(x,y) dxdy$$

- Impedance sub-matrix denotes the x/y-directed testing of electric field produced by x/y-directed current basis elements
- Voltage sub-matrices refer to x- and y-directed testing of incident electric field.
- Current sub-matrices are respectively the unknown electric current expansion coefficients which can be obtained as follows.

$$[I] = [Z]^{-1}[V]$$

Equivalent Circuit Parameter Extraction

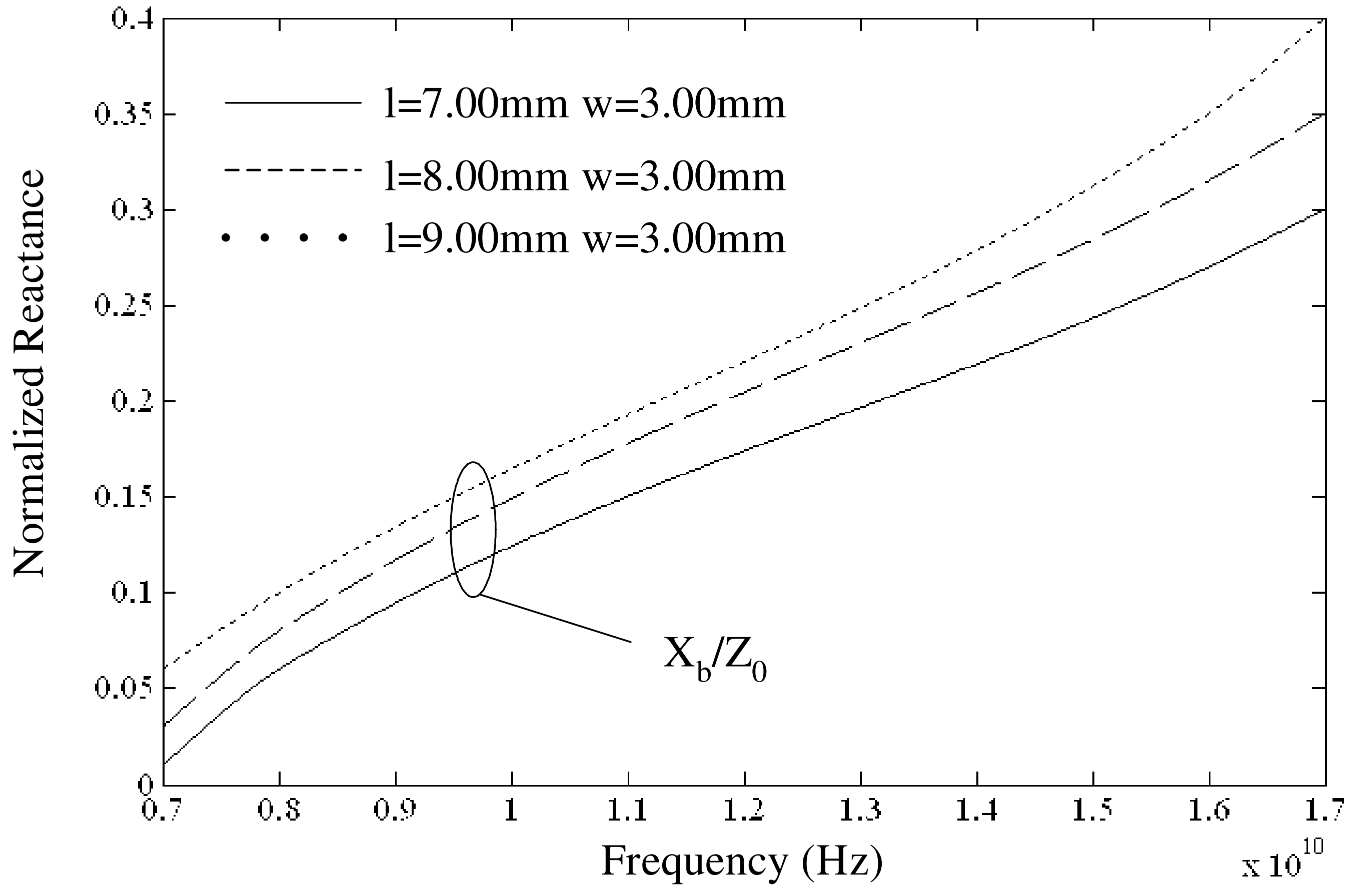
[S] → [ABCD] → [Z] or [Y]



(a) π-equivalent and (b) T-equivalent circuit network

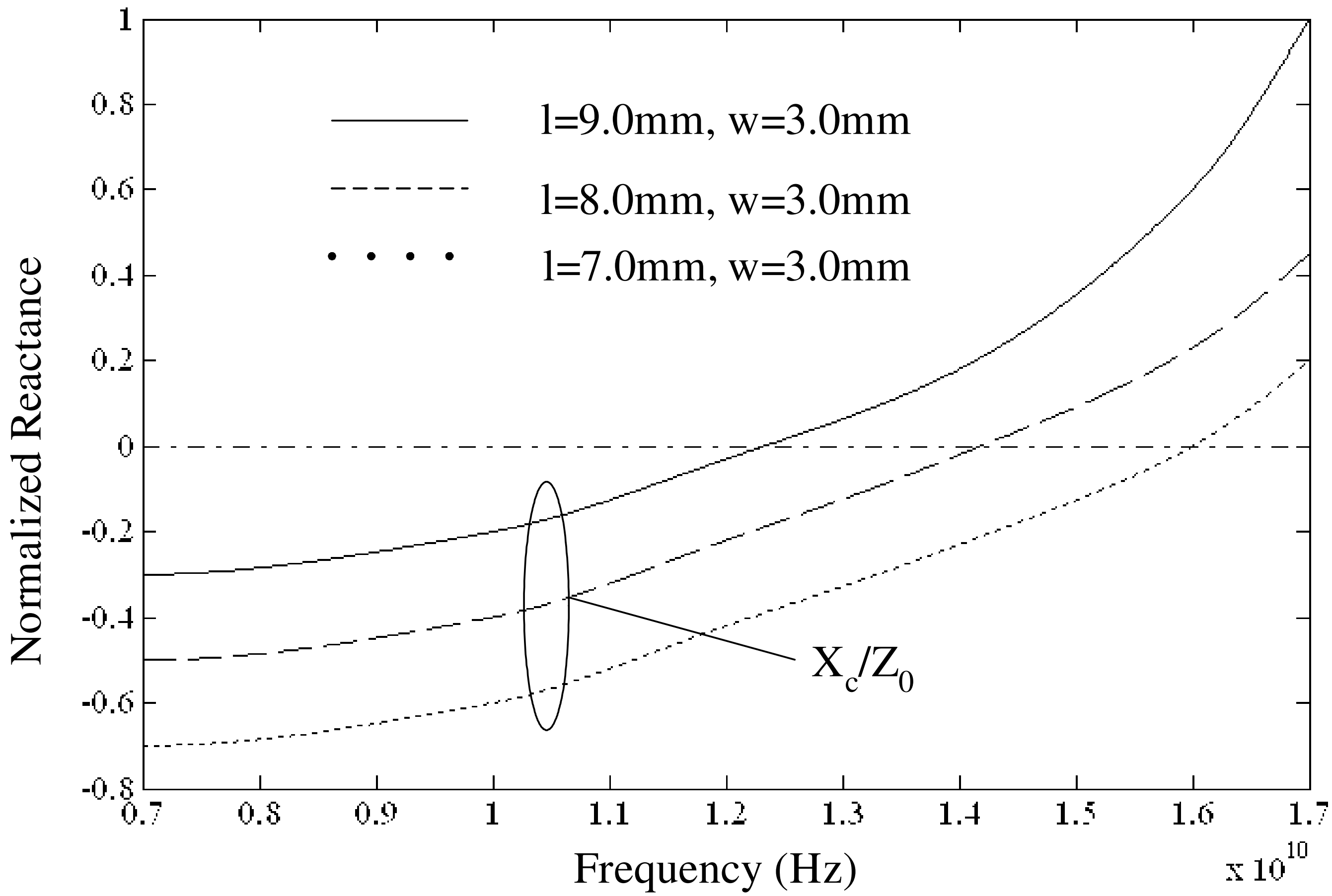
From the equivalent circuit network, we can extract the equivalent circuit of the waveguide discontinuity

Equivalent circuit for printed strip



Normalized X_b versus frequency

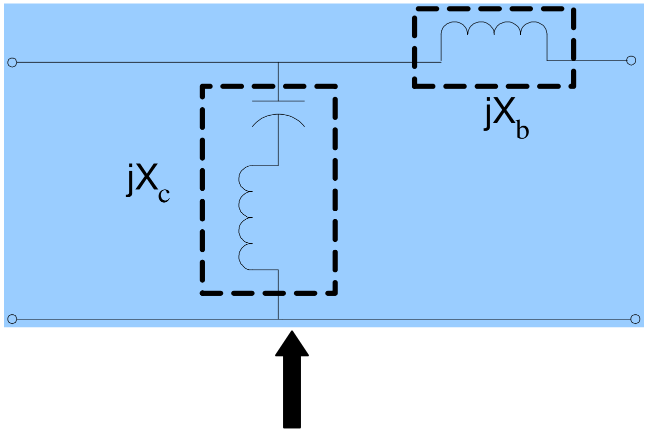
Equivalent circuit for printed strip



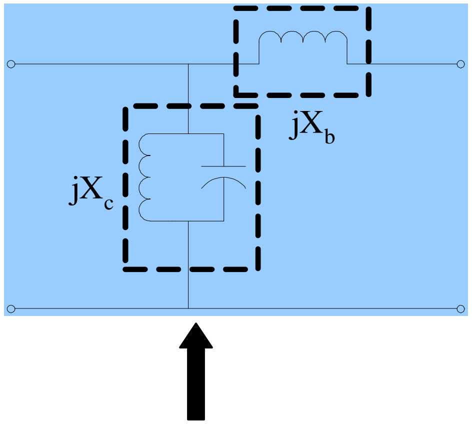
Normalized X_c versus frequency

Equivalent circuit for printed strip/slot

- Normalized X_a is very small and can be neglected in the equivalent T-network.
- Hence, the equivalent circuit is as show in Figure (left) below.
- Similarly, we can get the equivalent circuit for the printed slot from the Z parameters of the T-network as shown in Figure (right) below.

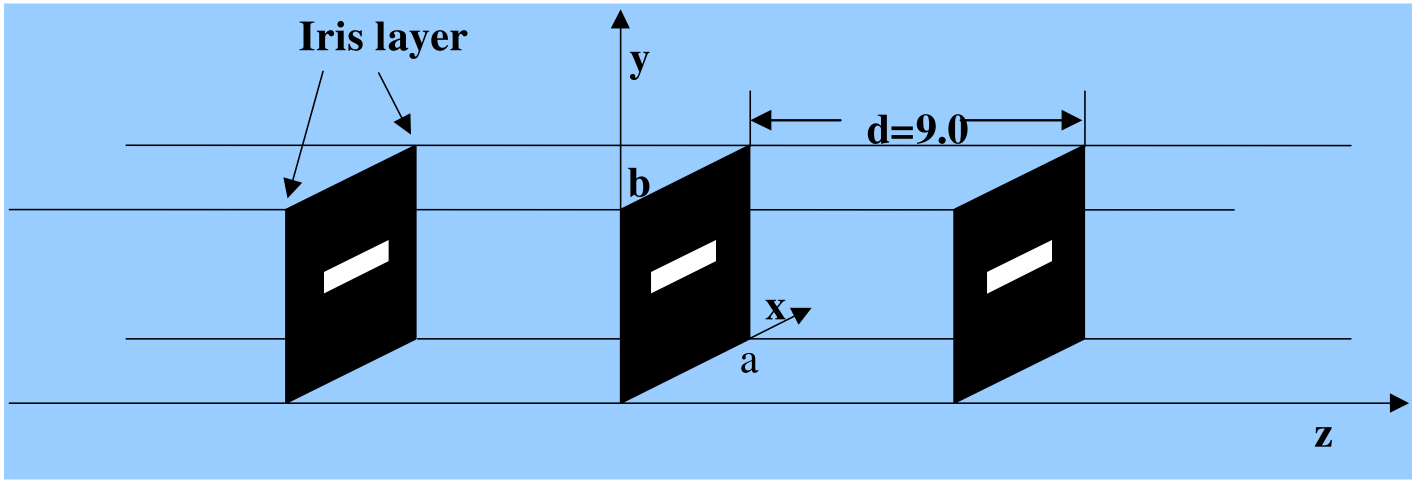


Eq. Ckt. for printed strip



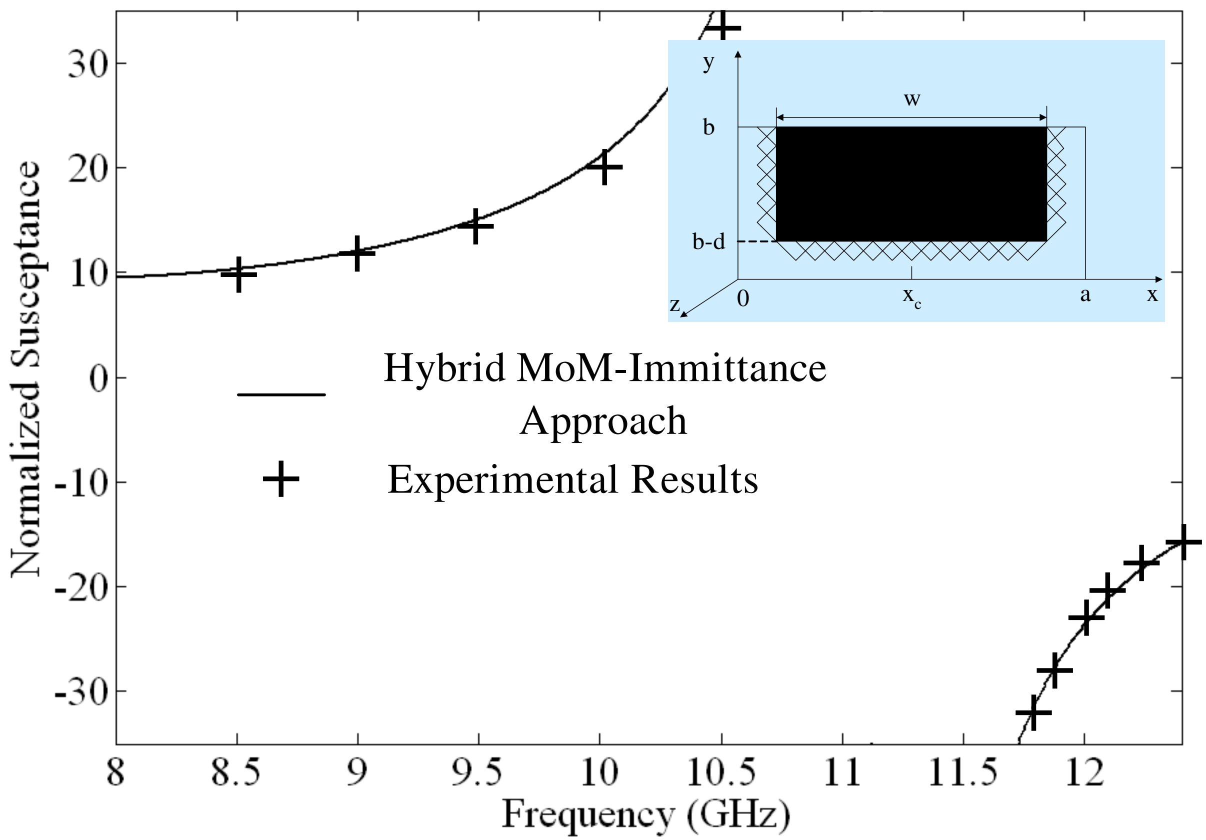
Eq. Ckt. for printed slot

Efficiency Comparison with Finite Element Method (FEM)



- A three-stage waveguide filter composed of resonant iris (w=15.5mm and l=2.7mm)
- For HMIA, overall CPU time on Pentium 4 PC @1.7 GHz (43.7 minutes).
- For High Frequency Structure Simulator (HFSS), with a λ-refinement based upon a target frequency of 11 GHz, discrete sweeps were run between 7 and 17 GHz. Overall CPU time on the same PC configuration was 13.7 hours.

Experimental Validation of a Wide Resonant Strip



Normalized susceptance of a centered strip of w=0.280 inch and d=0.360 inch (inset, Cross section)

Section II

Guided-wave Characteristics[2]

2) R. S. Kshetrimayum and L. Zhu, "Guided-wave Characteristics of Waveguide Based Periodic Structures Loaded with Various FSS Strip Layers," *IEEE Transactions on Antennas and Propagation: Special Issue on Artificial Magnetic Conductors, Soft/Hard Surfaces, and other Complex Surfaces*, Vol. 53, No. 1, pp. 120-124, Jan. 2005

Per-unit Length Transmission Parameters

- Constitutes complex propagation constant ($\gamma=\alpha+j\beta$) and complex wave impedance ($Z_0=Re(Z_0)+jIm(Z_0)$) unlike the Brillouin diagram which shows only β
- Can be obtained from the ABCD parameters of a unit cell
- It gives a more complete picture of frequency-dependent propagation characteristics of periodic waveguide structures from which we can infer their possible applications

Propagation

$$\cos\beta p = \frac{A_u + D_u}{2}$$

Attenuation

$$\cosh\alpha p = \frac{A_u + D_u}{2}$$

Wave impedance

$$\frac{Z}{Z_0} = \pm\sqrt{\frac{B}{C}}$$

Important terms

Phase velocity of a wave is the rate at which phase of wave propagates in space

$$v_p = \frac{\omega}{k}$$

The group velocity of a wave is the velocity with which the overall shape of wave amplitude propagates

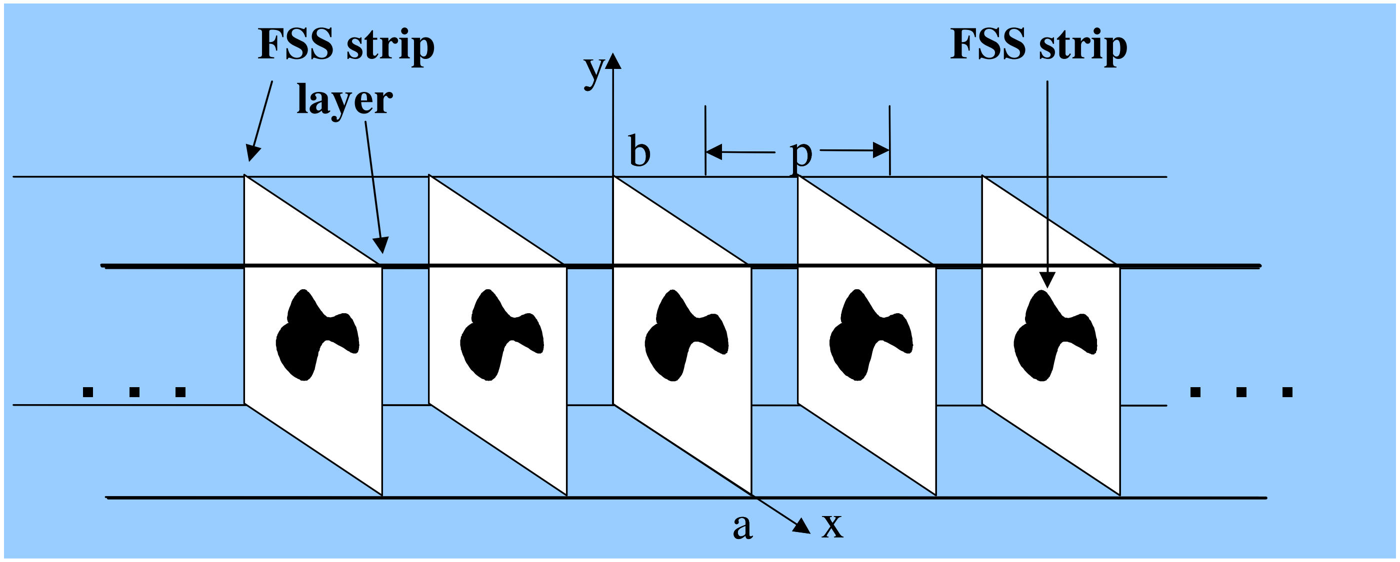
$$v_g = \frac{\partial \omega}{\partial k}$$

Slow wave ($\beta/k_0>1$) and fast wave ($\beta/k_0<1$)

In forward wave, both the phase velocity and group velocity propagates in the same direction whereas they propagate in opposite direction for backward wave

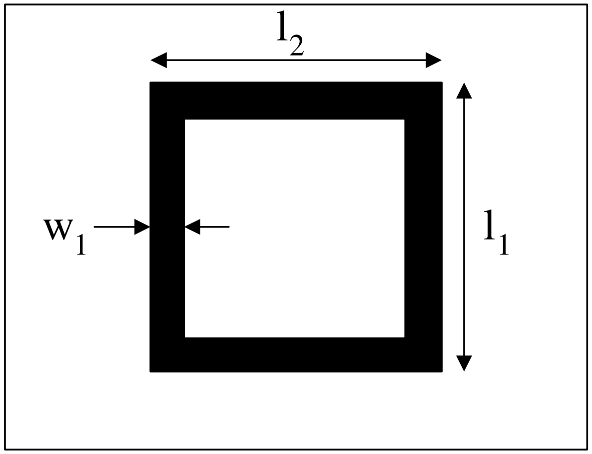
FSS strip printed periodic waveguide

- 3-D geometry of an infinite-extended waveguide based periodic structure loaded with any arbitrary FSS strip layers.
- Periodicity p of printed periodic waveguide structure is chosen as 4.00mm.
- X-band waveguide (a=22.86mm and b=10.16mm)



Square Loop FSS strip printed periodic waveguide

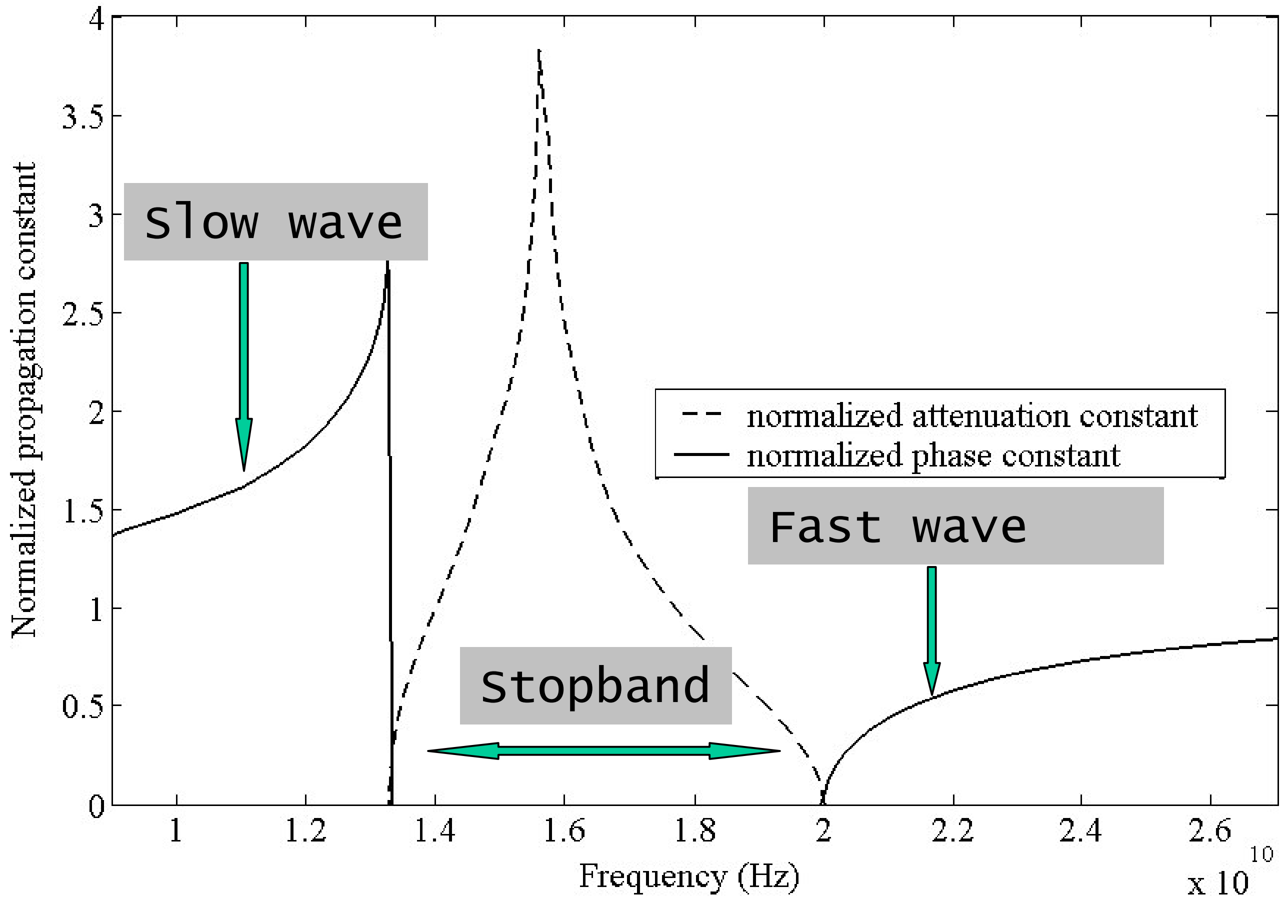
dimensions of strip are chosen as
l_1=7.0mm, l_2=7.00mm and w_1=2.00mm



Front view

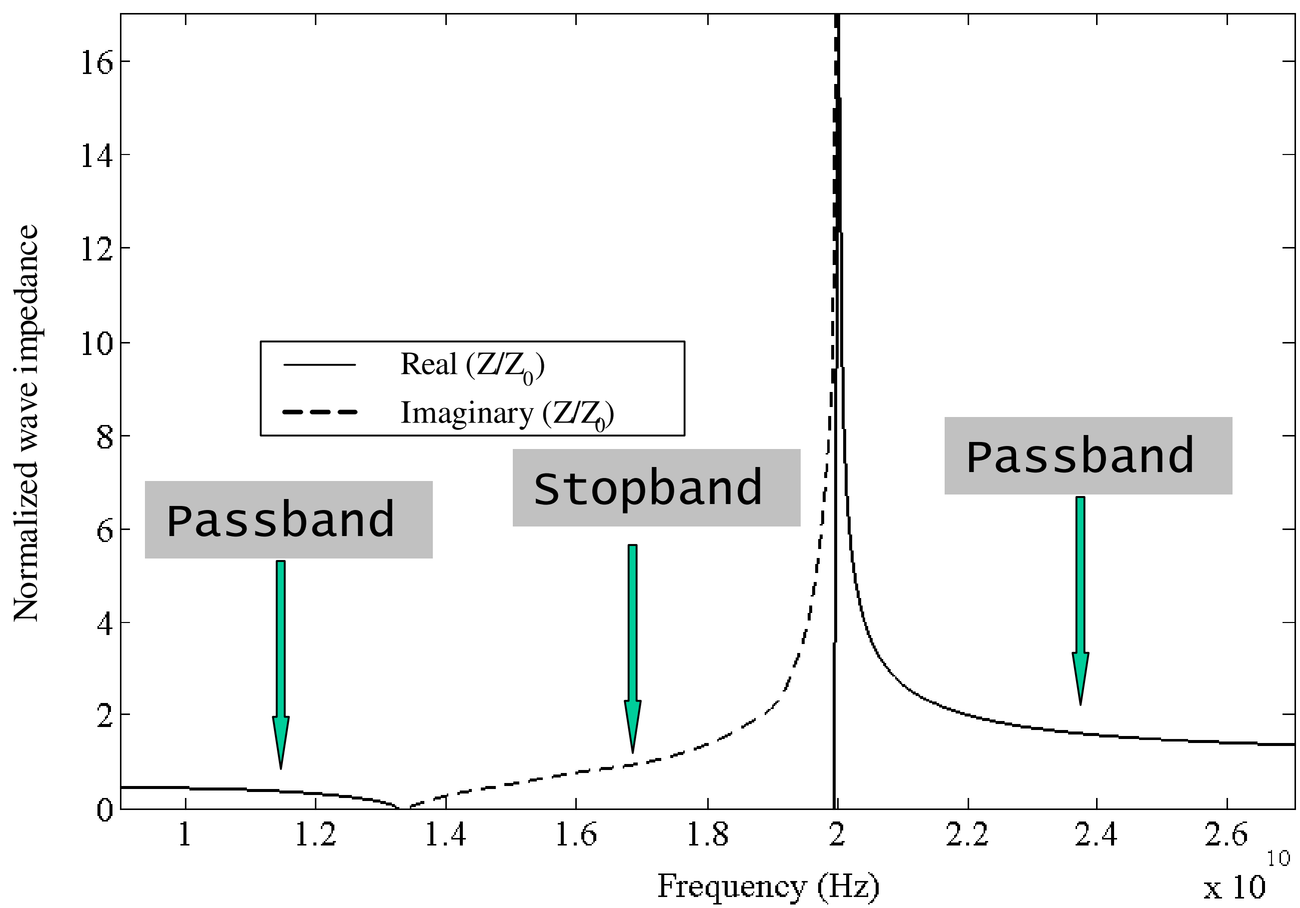
Square Loop FSS strip printed periodic waveguide

Normalized propagation constant ($\gamma/k_0=\alpha/k_0+j\beta/k_0$)



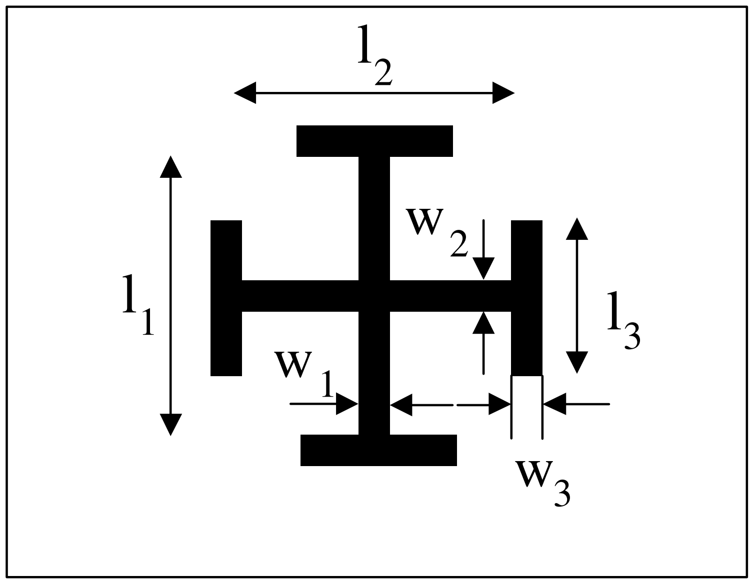
Square Loop FSS strip printed periodic waveguide

Normalized wave impedance (Z/Z_0)



Jerusalem Cross FSS strip printed periodic waveguide

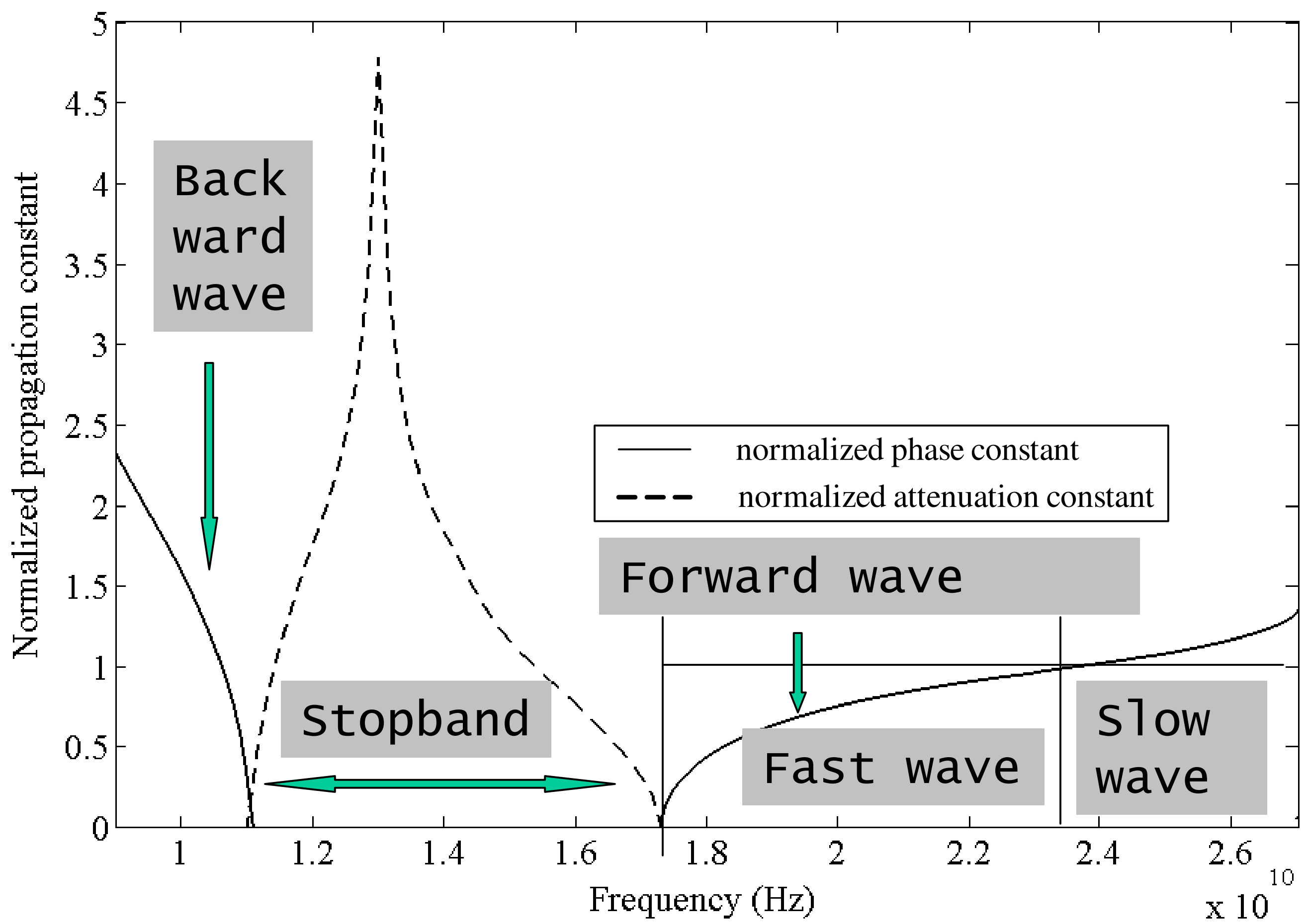
l_1=7.0mm, l_2=7.00mm, l_3=3.50mm, w_1=2.00mm, w_2=2.00mm and w_3=1.00mm.



Front view

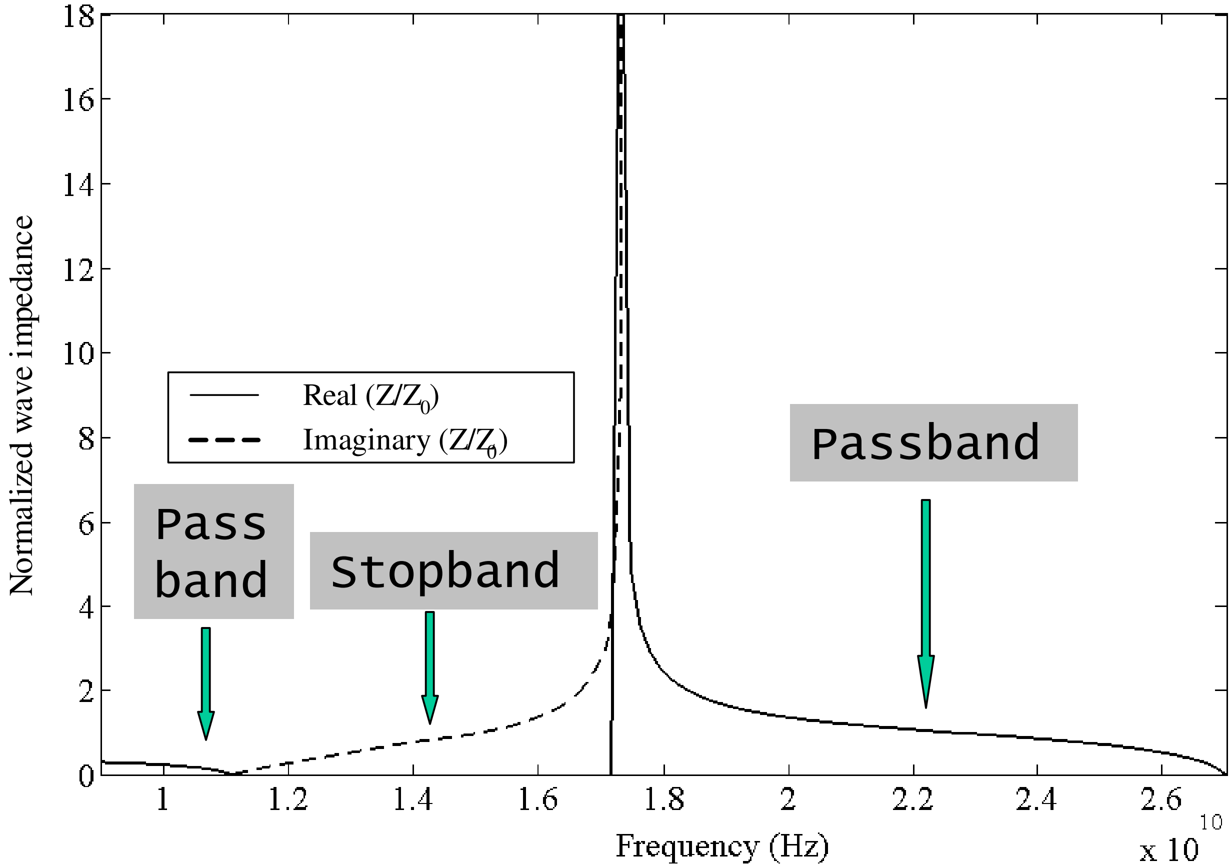
Jerusalem Cross FSS strip printed periodic waveguide

Normalized propagation constant ($\gamma/k_0=\alpha/k_0+j\beta/k_0$)



Jerusalem Cross FSS strip printed periodic waveguide

Normalized wave impedance (Z/Z_0)



Section III

Applications[3456]

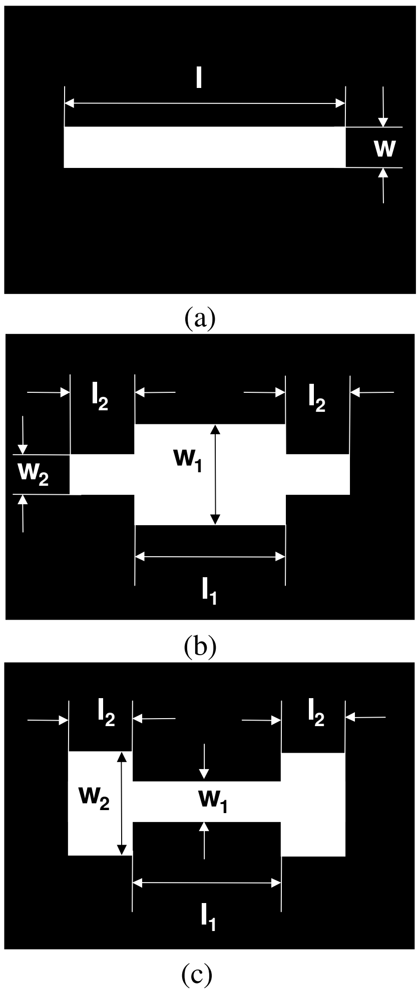
3) R. S. Kshetrimayum and L. Zhu, "**Novel SIS Resonator Waveguide Filters**," *International Journal of RF and Microwave Computer-Aided Engineering,* Nov. 2005.

4) R. S. Kshetrimayum, "**Printed periodic waveguide structures: full-wave characterization, guided-wave characteristics and applications**," *PhD thesis, Nanyang Technological University, Singapore.*

5) R. S. Kshetrimayum and L. Zhu, "**EBG Design using FSS elements in rectangular waveguide**," submitted to *IEE Proc. Microwaves, Antennas and Propagation*.

6) R. S. Kshetrimayum, K. J. Vinoy and L. Zhu, "**Equivalent material parameter extraction of double strip loaded waveguide**," *IEICE Electronics Express*, Vol. 2, No. 5, March 10, 2005, pp. 165-169.

Novel Stepped Impedance Slot (SIS) Resonator Waveguide Filters



Front view of waveguide loaded with

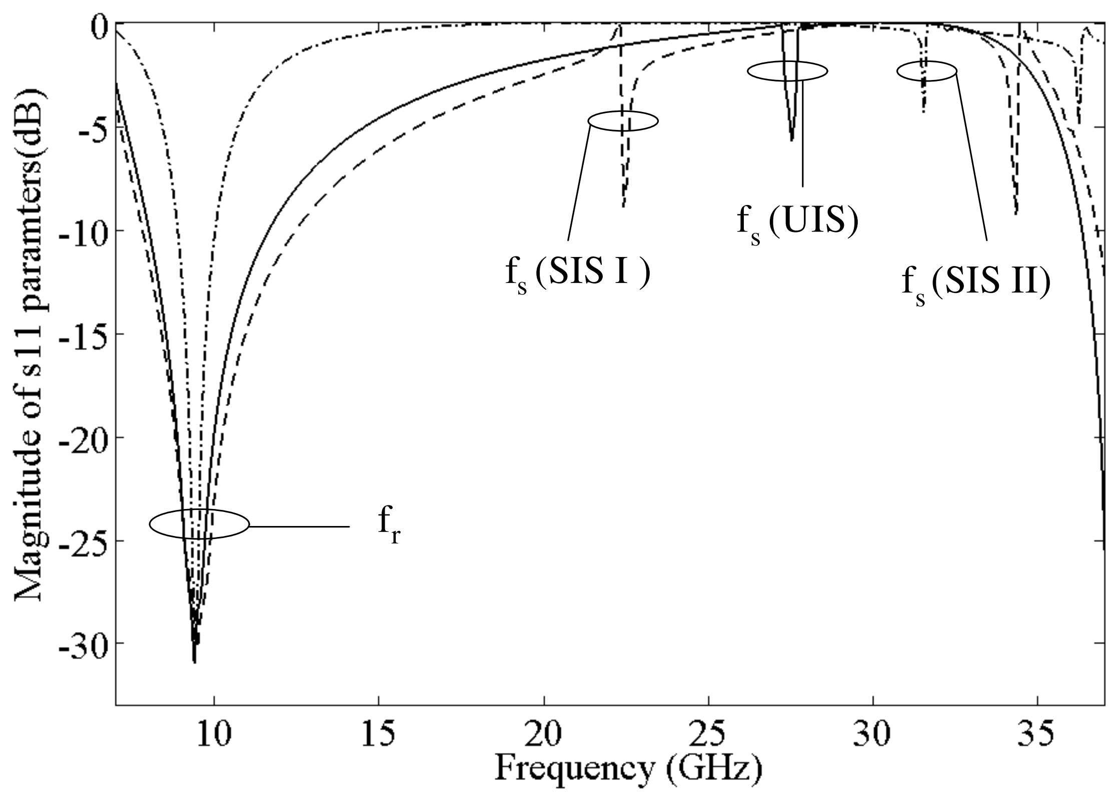
(a) Uniform Impedance Slot (UIS) resonator

(b) SIS resonator I

(c) SIS resonator II

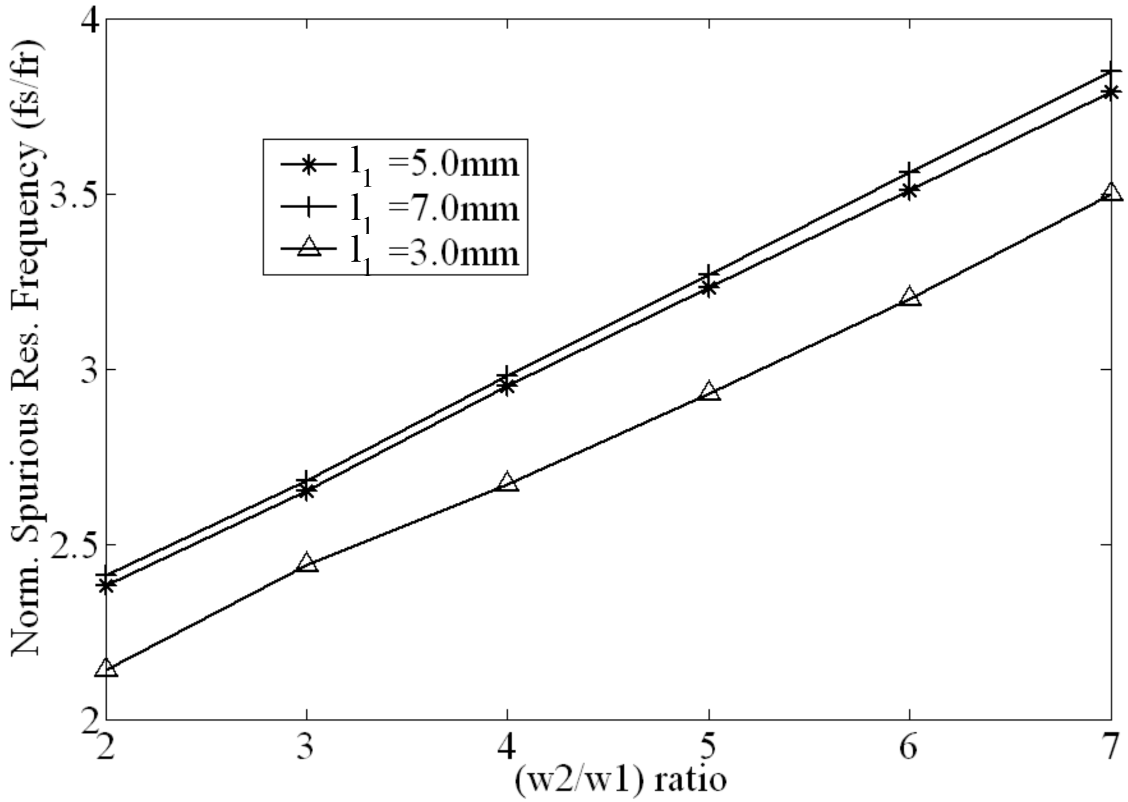
Aim is to explore such SIS resonators to increase the frequency band stop between the fundamental (f_r) and spurious harmonic (f_s) resonant frequencies

SIS and UIS Resonators



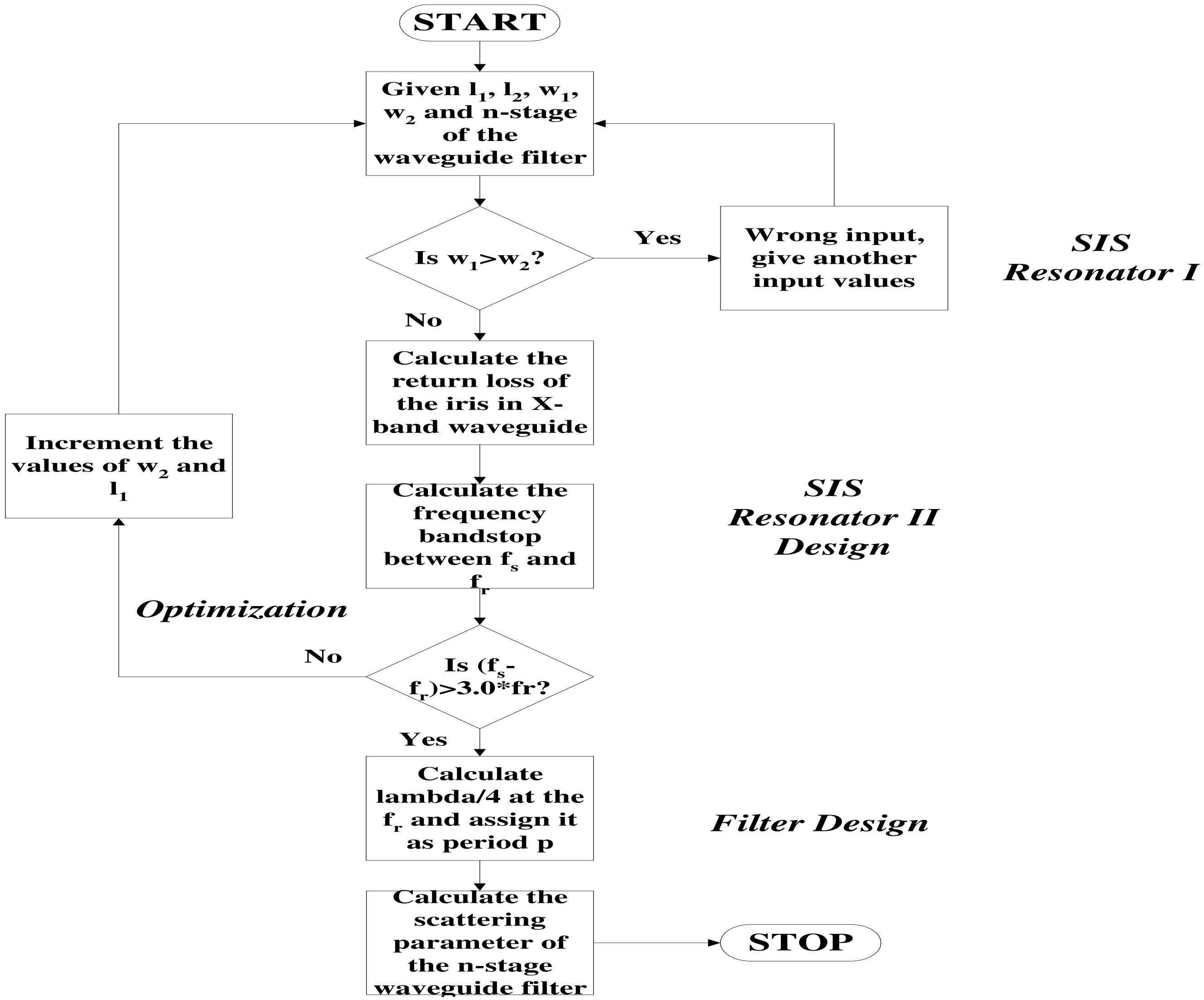
Keeping the f_r fixed, we check the furthest f_s for the three cases. We can infer that SIS resonator II gives the widest (f_s-f_r) frequency band stop.

SIS resonator II



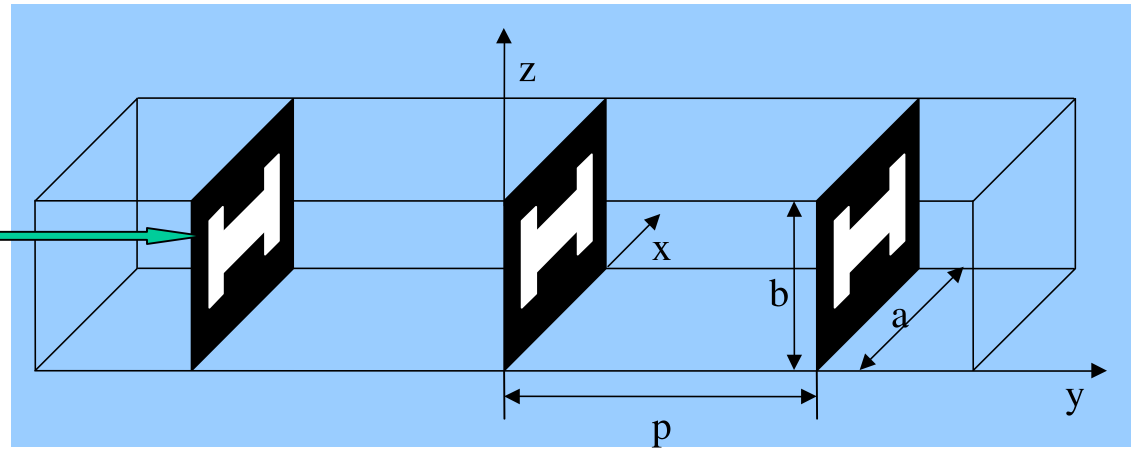
Characterization of SIS resonator II with respect to various parameters viz. w_2, w_1 and l_1 in terms of normalized spurious resonant frequency (f_s/f_r).

Algorithm for designing SIS resonator waveguide filters



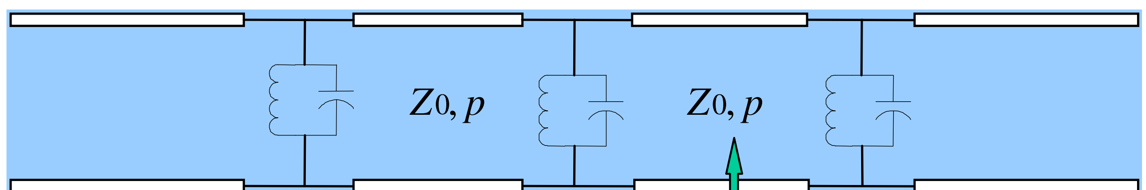
Harmonic suppressed waveguide band pass filters

SIS Resonators II



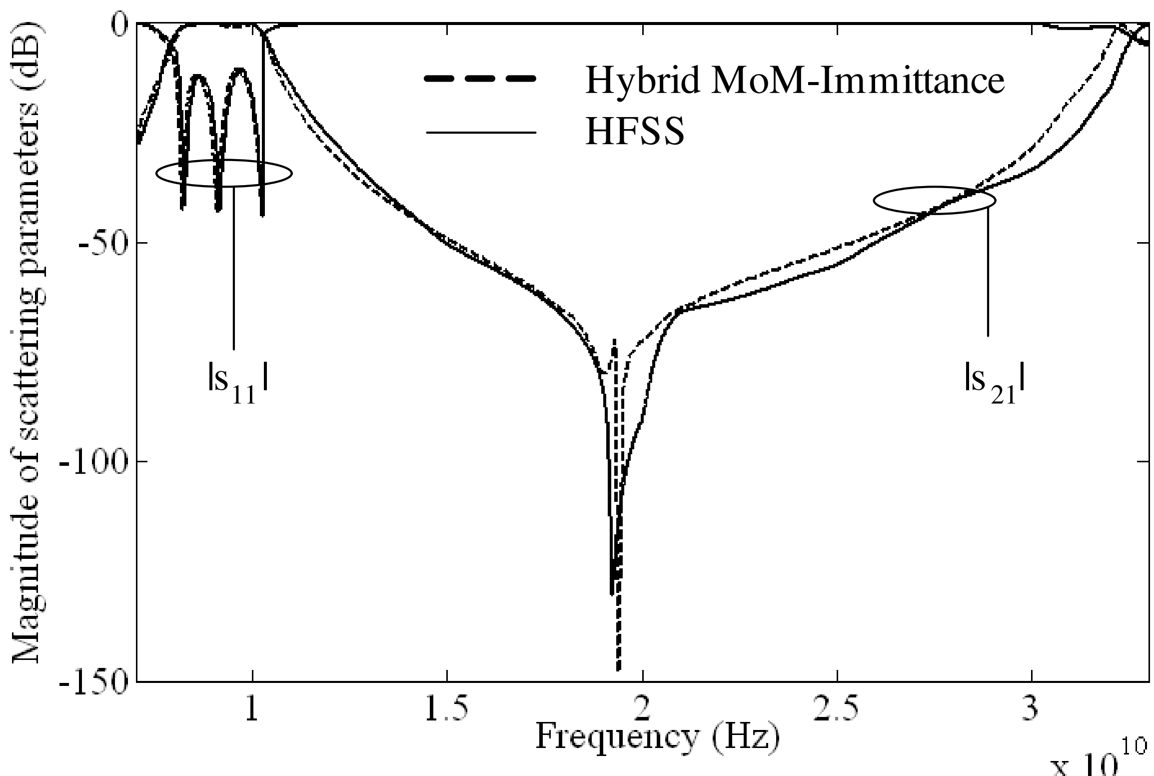
3-D Geometry

p=8.23mm;
SIS resonator II
(w_1=1.0mm, w_2=9.0mm, l_1=3.0mm &l_2=3.5mm)



Eqt. Ckt. Network ($p \approx \lambda_g/4$)

Filter Performances



- Bandwidth 23.8%, return loss < -10dB, mid-band frequency 9.3GHz.
- Out-of-band rejection bandwidth ~23GHz and mid-stop band attenuation < -100dB at 19.4 GHz.
- response at two sides of passband much steeper.

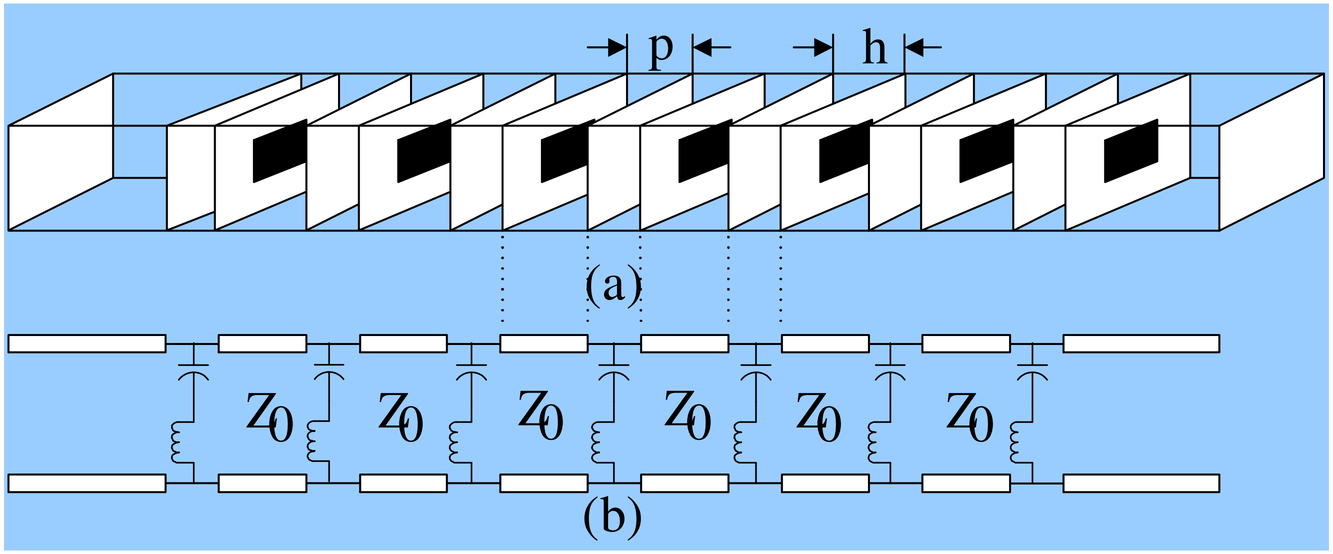
Waveguide Based EBG Structures

- A waveguide based EBG structure is constructed by periodically loading rectangular waveguide with FSS strip layers printed on dielectric substrate.

- The various parameters which may control the EBG performances of FSS square strip printed periodic waveguide structure are:

  - Dimension of FSS square strip
  - Dielectric constant of dielectric layer on which the FSS elements are printed
  - Thickness of the dielectric layer
  - Period of the periodic waveguide structure
  - Number of unit/cells

Effect of various parameters on the EBG performance



Periodic waveguide structures as EBG transmission media (a) Geometry (b) Equivalent circuit network

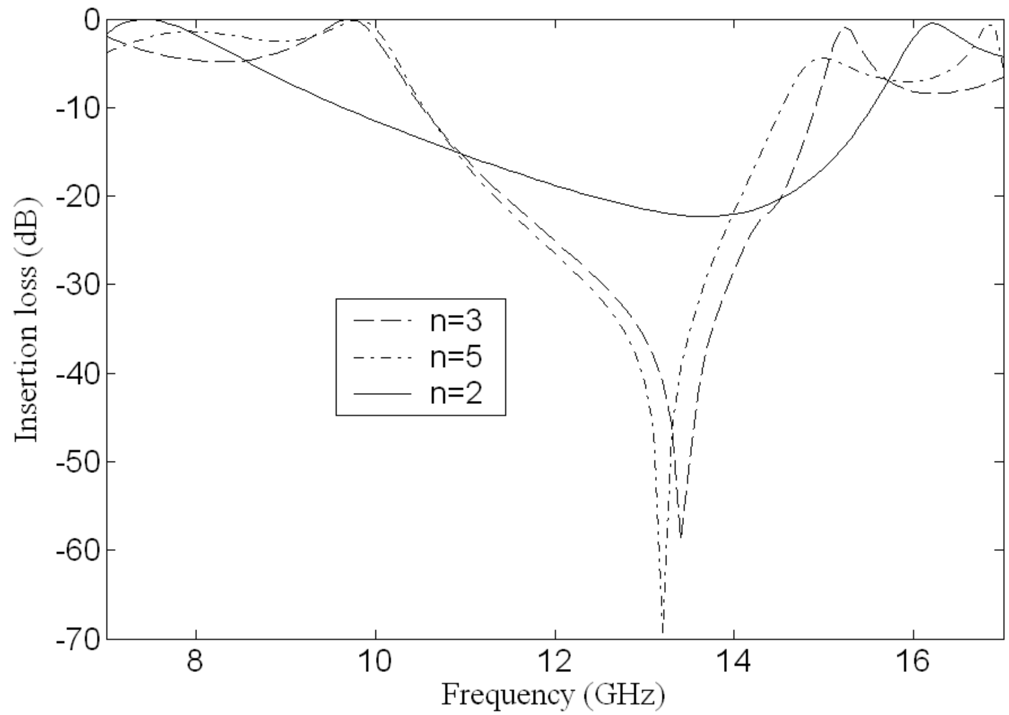
The square FSS strip elements are printed on a dielectric layer of ϵ_r=3 and thickness h=1mm. The waveguide dimension are (22.86mm×10.16mm) and the dimensions of FSS strip elements are chosen as a=7mm. EBG performance of a single unit/cell depending on various parameters have been investigated.

Effect of various parameters on the EBG performance

a	9mm	8mm	7mm
EBG width	(18.4-8.0)/13.2	(18.2-12.2)/15.2	(18.2-14.3)/16.2
	78.78%	39.47%	24%
Relative permittivity	3	4	7
EBG width	(18.2-14.3)/16.25	(16.7-12.7)/14.7	(14.8-10.8)/12.8
	24%	27.2%	31.25%
h	1mm	2mm	3mm
EBG width	(18.2-14.3)/16.25	(16.4-13.8)/15.1	(15.8-13.8)/14.8
	24%	17.21%	13.51%
p	4.8mm	5.8mm	6.8mm
EBG width	(15.5-9.6)/12.55	(15.3-10.1)/12.7	(15.2-10.8)/13.0
	47.01%	40.94%	33.84%

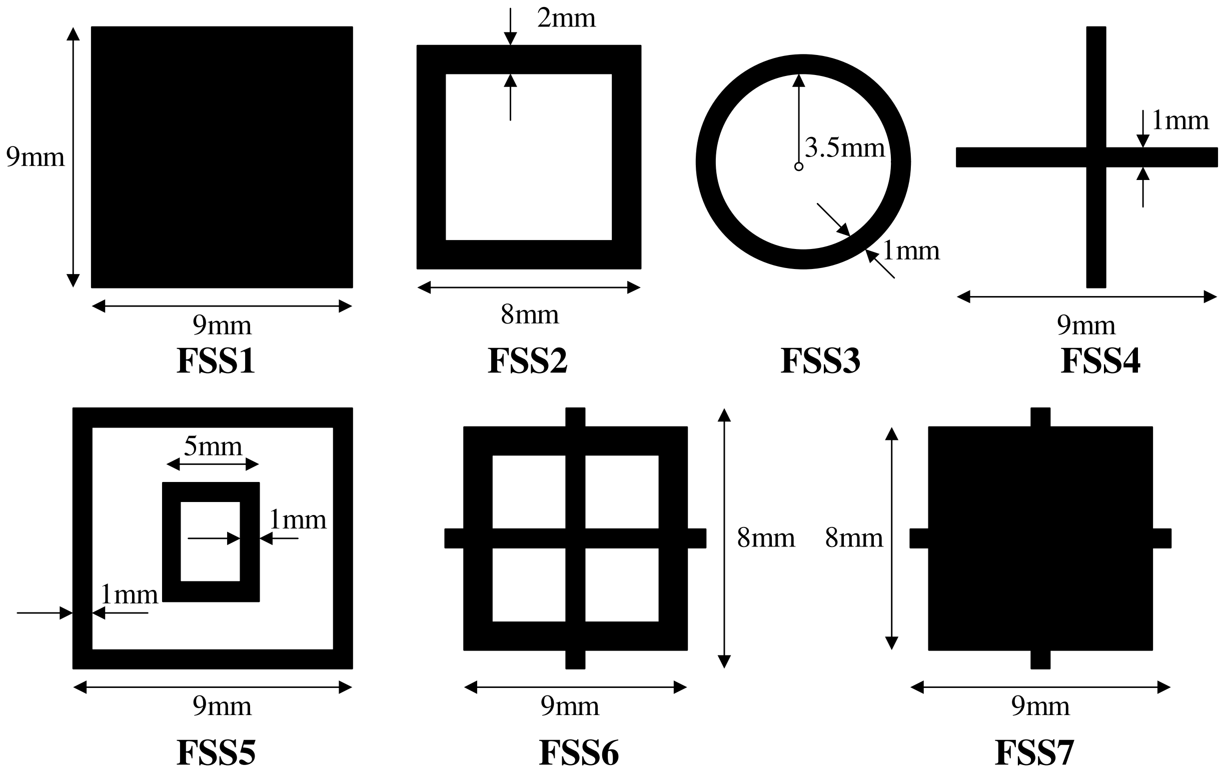
-10 dB insertion loss EBG width versus various parameters

Effect of number of unit cells on the EBG performance



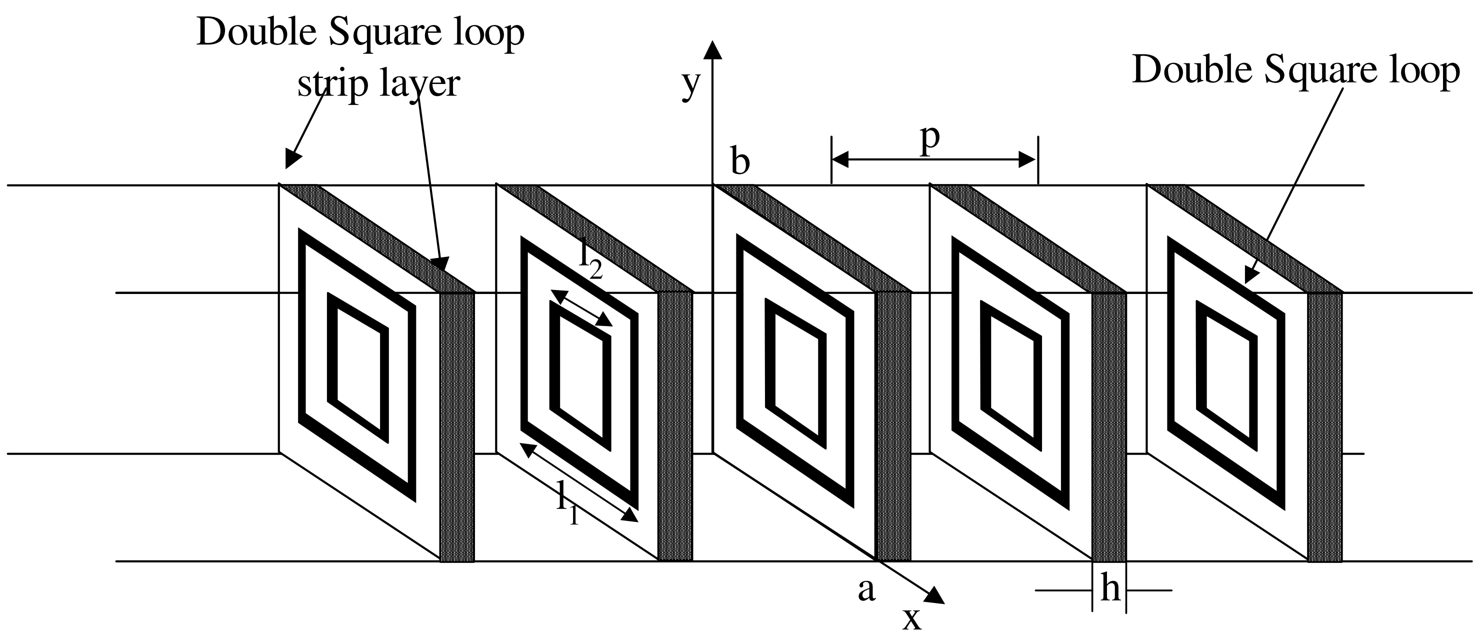
Insertion loss (S_{21}) for periodic waveguide structure with number of unit cells n=2, 3 and 5 for a fixed periodicity p=4.8mm. As n increases, S_{21} goes into deep rejection band. There is also slight decrease in the EBG width as the number of unit/cells increases.

Improving the Roll-off Characteristics



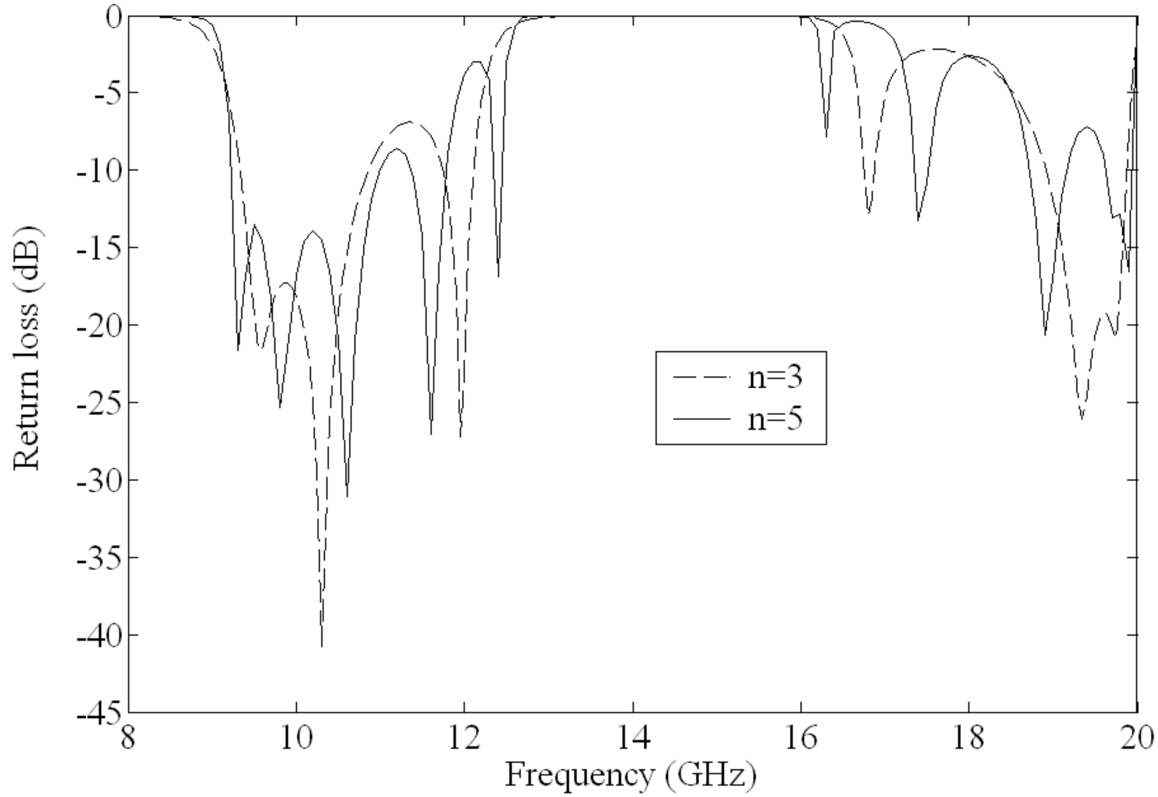
Several FSS strip structures loaded waveguide have been investigated to improve the roll-off factor. The best insertion loss characteristics for improving the roll-off characteristics is observed for FSS 5 i.e., double square loop FSS structure

Improving the roll-off characteristics



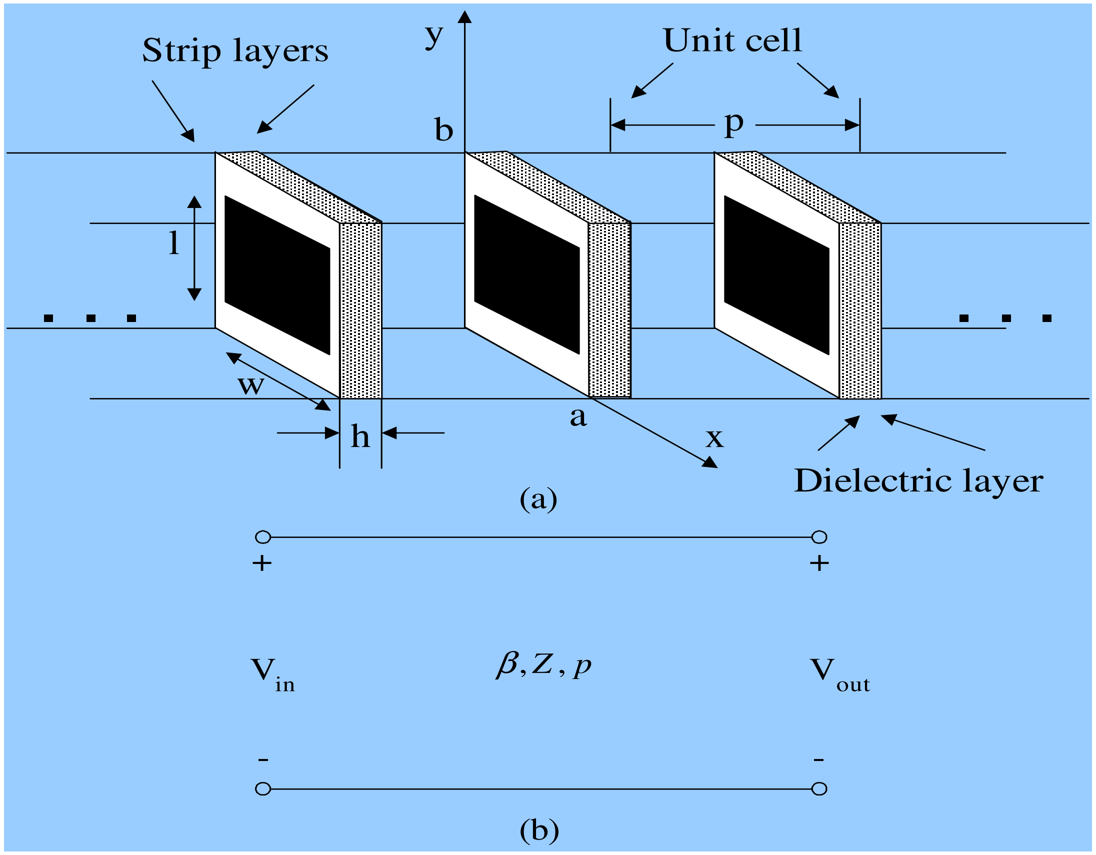
Let us study the effect of number of unit/cells on the EBG performance specially the roll-off characteristics. The dimensions of the double square loops are chosen as l_1=9mm and l_2=5mm. Both the square loops have thickness 1mm. The period p is chosen as 5.58mm and thickness of the dielectric layer of ϵ_r=3 is taken as h=1mm.

Improving the roll-off characteristics



As n increases, the roll-off factor in the passband characteristics improves making it more suitable for use in harmonic suppression of waveguide filters and in design of band reject waveguide filters.

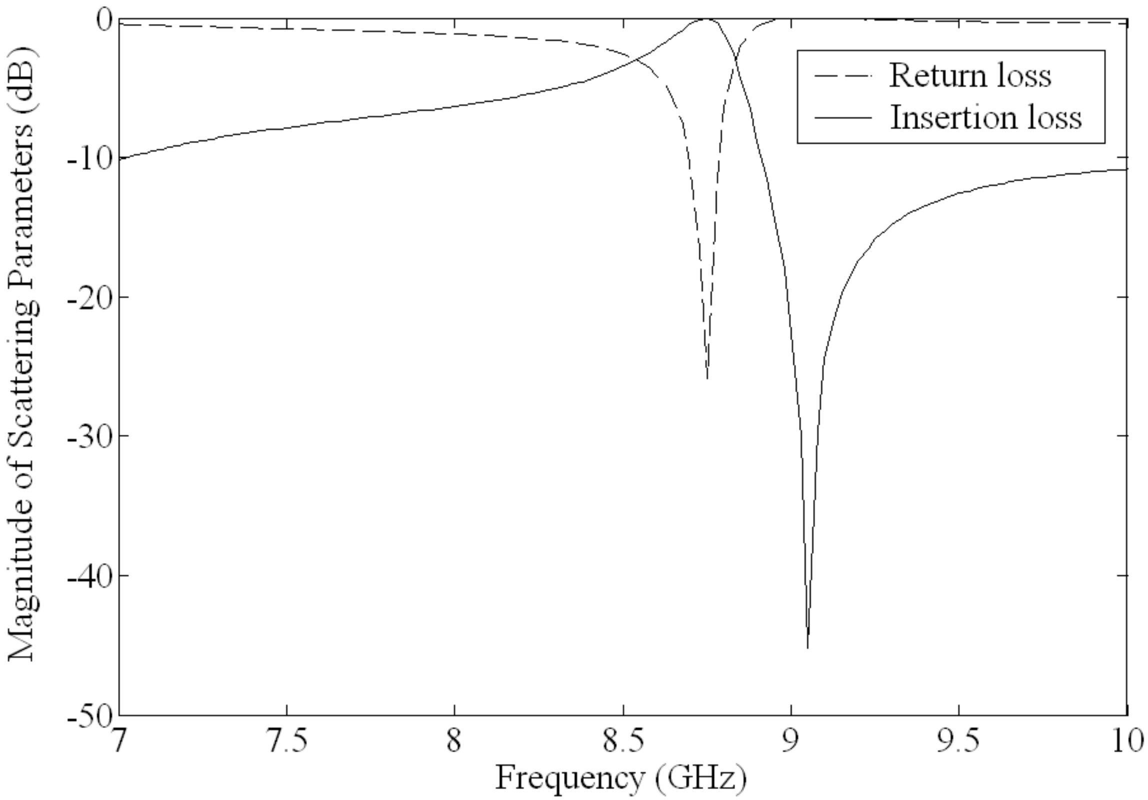
Novel Architecture for Waveguide based DNG Metamaterials



Rectangular waveguide loaded with double strips printed on a dielectric layer shows a DNG passband. Dimensions: w=8.00mm, l=6.00mm, h=1.00mm, p=3.00mm and ϵ=7.00.

(a) Proposed architecture for waveguide based DNG Metamaterials (b) Two-port network representation of a lossless transmission line (waveguide) of length p

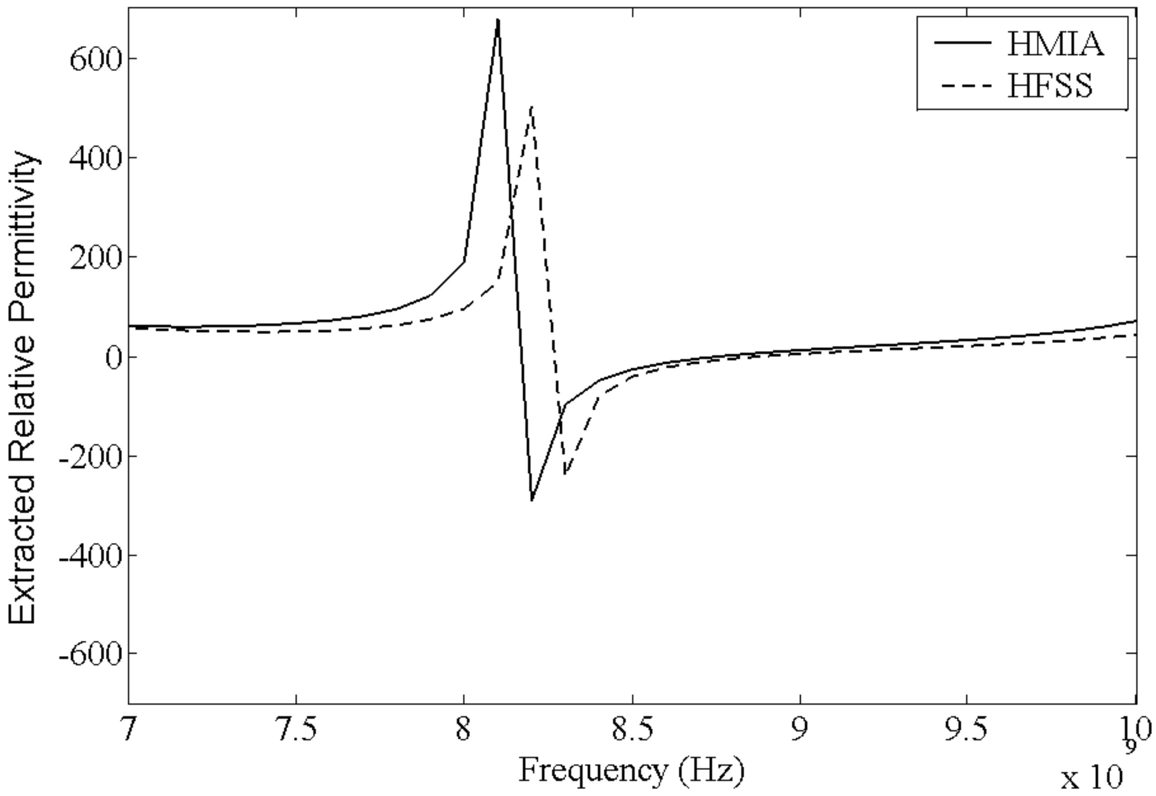
Double Negative Passband



DNG passband centered at 8.7GHz. -5dB insertion loss bandwidth 8.3-8.7GHz.

Extraction of Relative Permittivity

$$\varepsilon = \frac{C}{j\omega\varepsilon_0 pA}$$

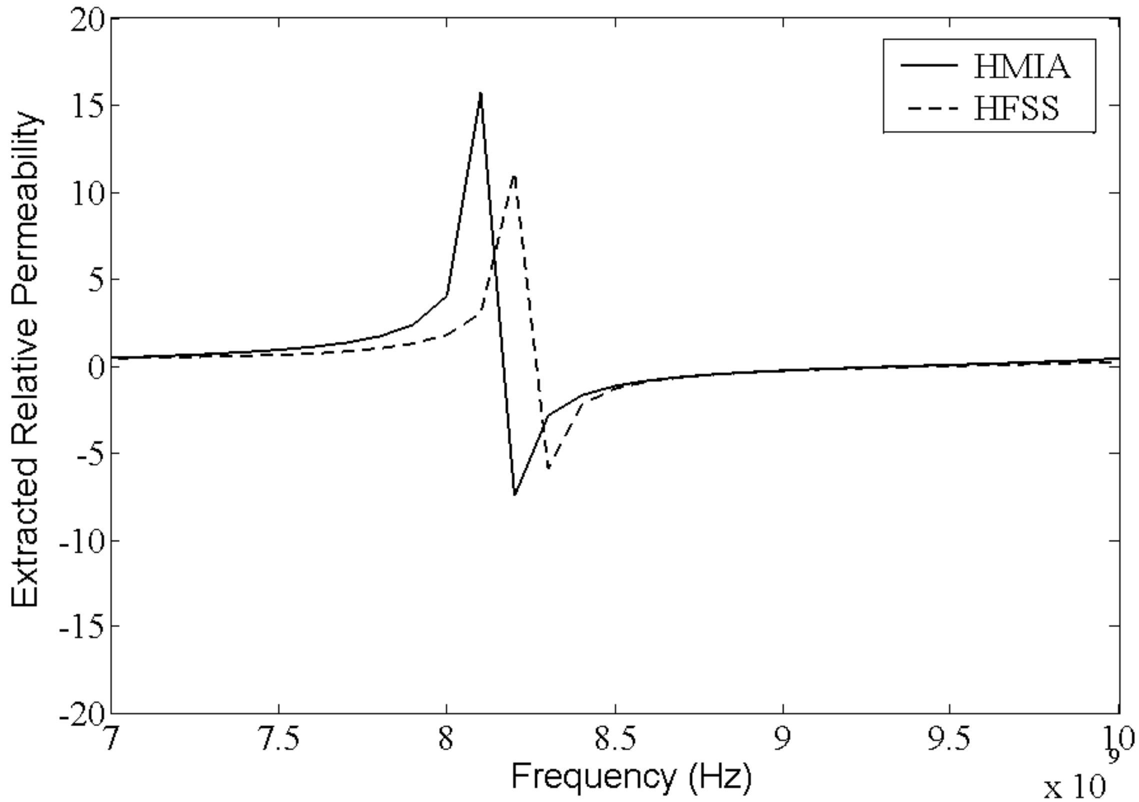


Extracted Effective Relative Permittivity

Amplitude of real part of relative permittivity ϵ_r reaches its most positive value, i.e., 500 at 8.2 GHz, passes through zero at 8.2GHz and then reaches its most negative value, i.e., -230 at 8.3GHz.

Extraction of Relative Permeability

$$\mu = \frac{B}{j\omega\mu_0 pA}$$



Extracted Effective Relative Permeability

Amplitude of real part of the relative permeability μ_r reaches its most positive value, i.e., 11 at 8.2 GHz, passes through zero at 8.27GHz and then reaches its most negative value, i.e., -7 at 8.3GHz.

Conclusions

- A hybrid numerical approach of MoM and Immittance approach has been developed for full-wave characterization of printed strips/slots.
- From the full-wave characterization of a single unit/cell, per-unit length transmission parameters or guided-wave characteristics for printed periodic waveguide structures loaded with various FSS elements have been numerically obtained and studied for various possible applications.
- Harmonic suppressed waveguide band pass filter has been designed using SIS resonators coupled by $\lambda/4$ waveguide impedance transformers.
- The effect of various parameters like periodicity, number of periods and FSS strips on the waveguide based EBG/PBG structures have been investigated.
- A novel architecture for waveguide based DNG metamaterials has been proposed.

Any questions!

Have a peaceful day!

Thanks.