Design of Narrowband Bandpass Filters using Dual-mode Open-loop Resonators

by

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10EC63R13

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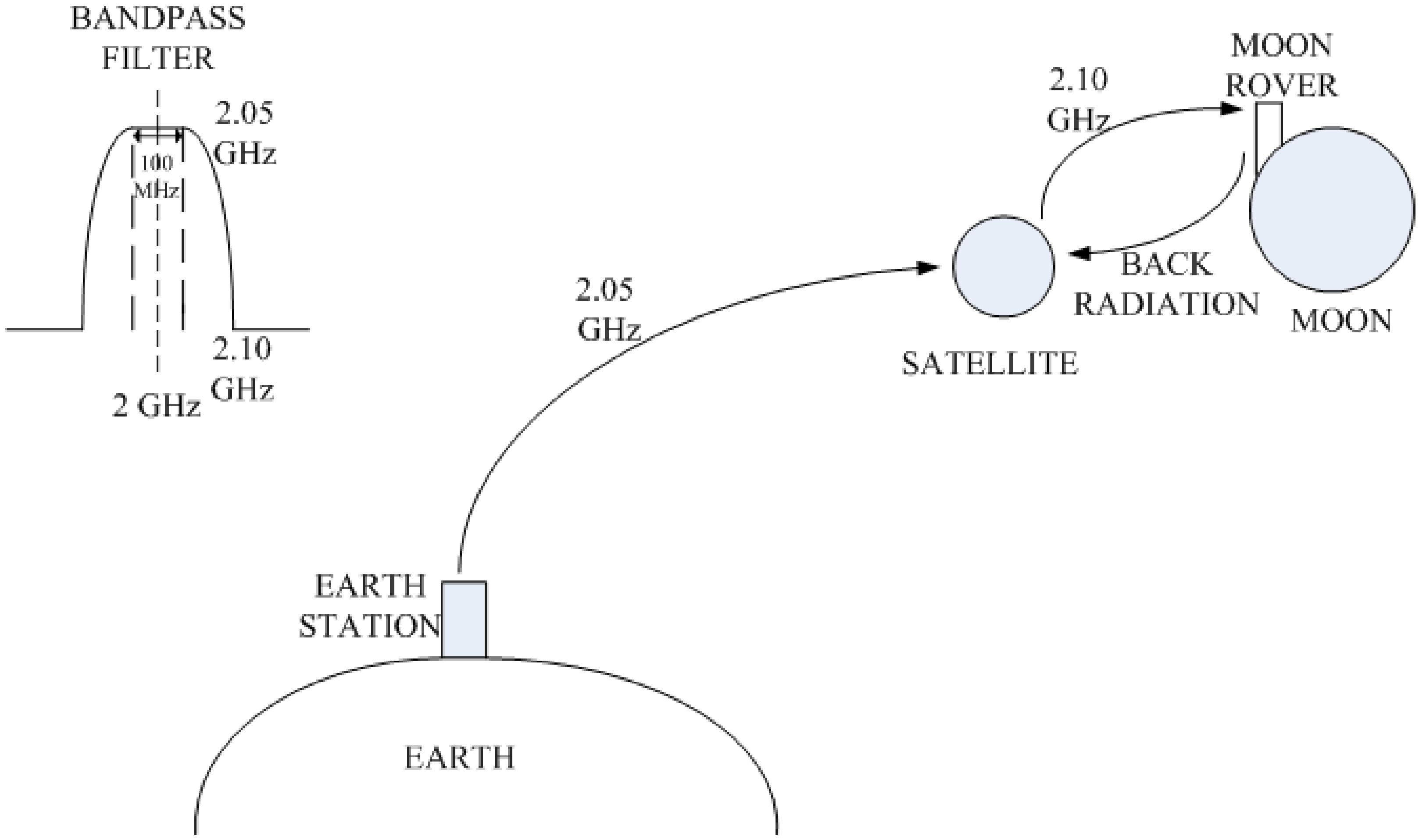
- Single-mode microstrip open-loop resonator
- Dual-mode microstrip open-loop resonator
- Filter design using dual-mode resonator
- Conclusion
- Future work
- Acknowledgement
- References

Motivation



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Objective

- Design a narrow bandpass filter with low insertion loss and higher selectivity at upper side of the passband.

- Filter specifications
  - Center Frequency = 2GHz
  - Pass band: 1.95GHz to 2.05GHz, (i.e. Bandwidth = 100MHz)
  - Insertion loss is better than 2dB at center frequency
  - Upper passband side skirt 70dB from 2.05GHz to 2.10GHz
  - Return loss is better than 15dB over the pass band.
- Selected Substrates
  - TMM10 -> relative dielectric constant 9.2, loss tangent 0.0022 and substrate height is 1.27mm on stripline configuration.
  - WOVEN TFG -> relative dielectric constant 2.5, loss tangent 0.0009 and substrate height is 3.175mm on stripline configuration.

Introduction

- Today communication system requires mainly low insertion loss and high selectivity.

- **Waveguide filters** or **dielectric loaded resonator filters** provides low insertion loss but leads to **increment** in size, weight and cost.

Fig. 1 Waveguide filter

Fig. 2 Dielectric loaded resonator filter

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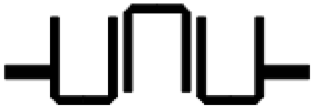
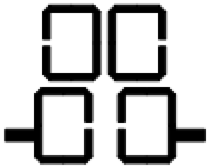
- For compact size **planar structure** is the better alternative , but leads to high conductor losses which are reduced by HTS materials.
- Different types of planar structures for filter design are

End-coupled filters

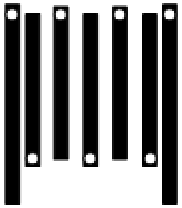
Parallel-coupled filters



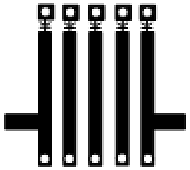
Hairpin filters



Open-loop resonators



Interdigital filter



Combline filter

- Open loop resonators are used for cross coupling filter design with compact size.

Single mode microstrip open-loop resonator

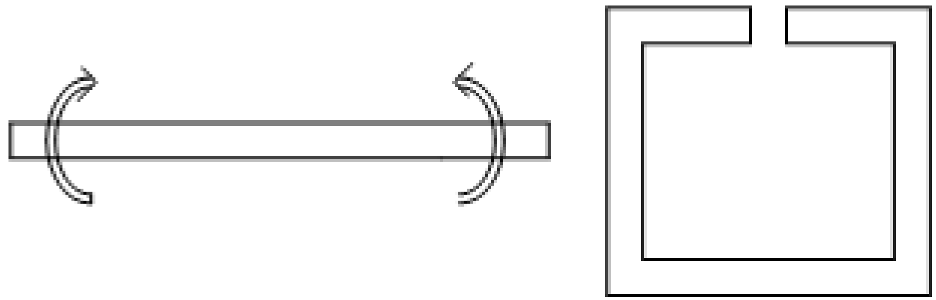


Fig. 3 The square open loop resonator can be obtained by folding a straight open resonator.

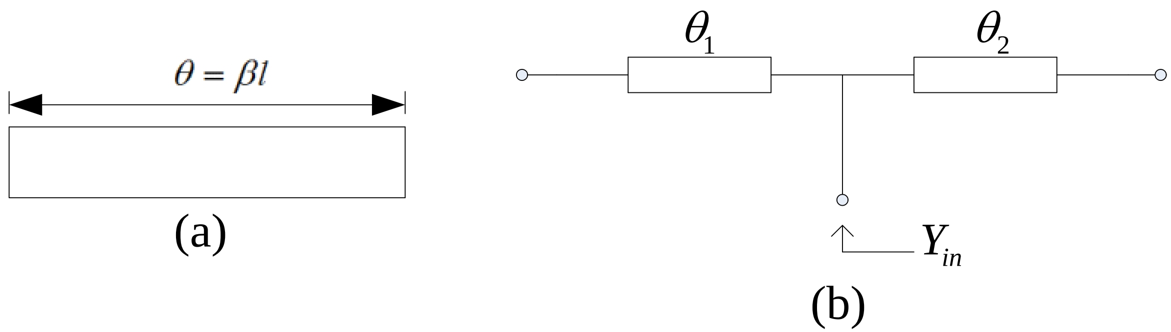


Fig. 4 Microstrip open resonator. (a) Top view of a microstrip straight resonator. (b) Equivalent circuit used to calculate the input admittance from an arbitrary point within the length of the resonator.

$$Y_{in} = jY_0(\tan(\theta_1) + \tan(\theta_2)) = jY_0 \frac{\sin(\theta_T)}{\cos(\theta_1)\cos(\theta_2)}$$

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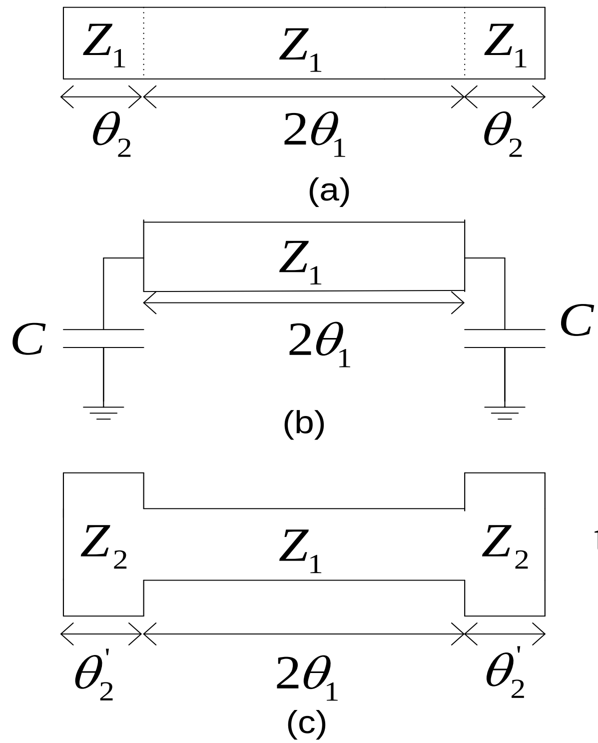

$$C = \frac{\tan(\theta_2)}{\omega Z_1}$$

$$\tan(\theta_2') = \frac{Z_2}{Z_1}\tan(\theta_2)$$

Fig. 5 Structural variation of a half-wave length type resonator. (a) Uniform impedance resonator (UIR). (b) Capacitor loaded UIR (c) Stepped impedance resonator (SIR) [5].

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- Semi open configuration and inhomogeneous dielectric medium of coupling structure, leads to characterize the coupling in terms of its resonant mode splitting.

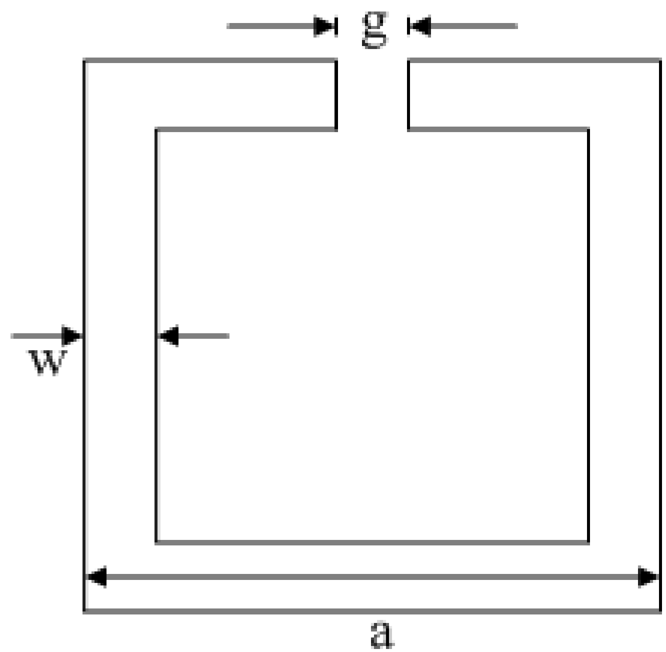

Fig. 6 Single-mode open-loop square resonator [1].

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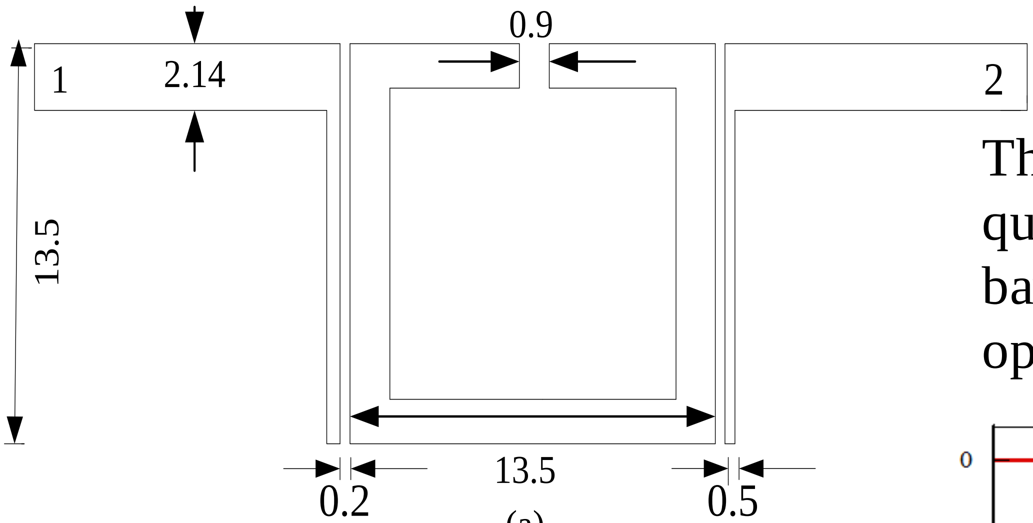
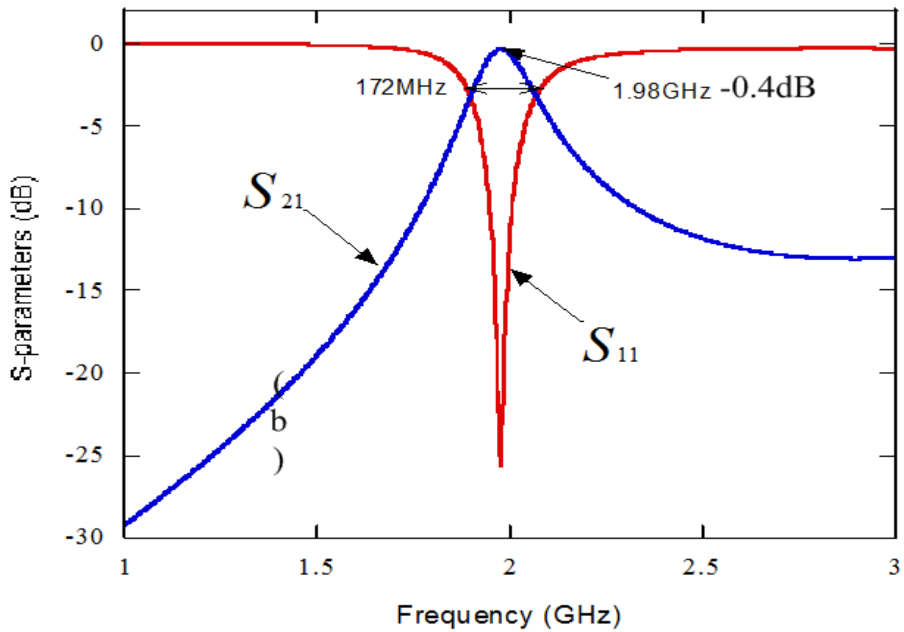


(a)

The center frequency is 1.98GHz, quality factor is 11.5 and bandwidth is 172MHz for the open-loop resonator.



(b)

Fig. 7 Single mode open-loop square resonator. (a) Simulation diagram showing week I/O coupling to the resonator (all dimensions are in mm). (b) Frequency response using Zeland [4].

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- Different orientation of identical microstrip open loop resonators are separated by ‘s’ and offset by ‘d’ leads to coupling structure.
- Three types of coupling takes place
  - Electric coupling, Magnetic coupling and Mixed coupling.

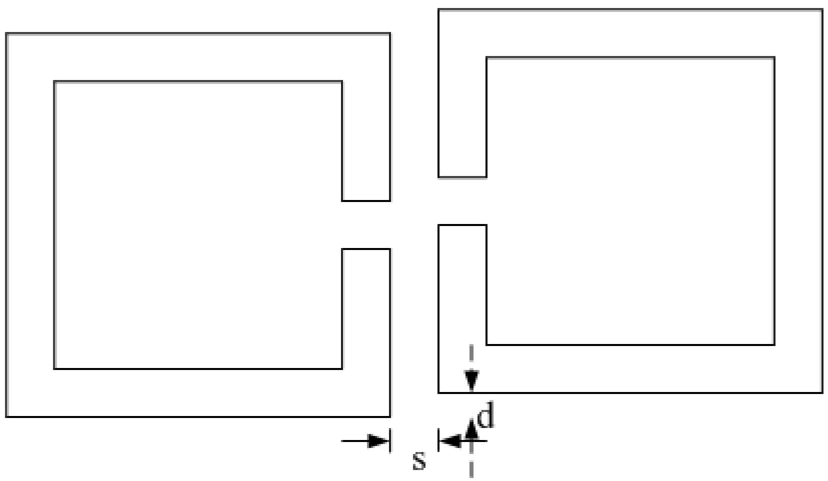

Fig. 8 Electrical coupling between two single-mode resonators [3].

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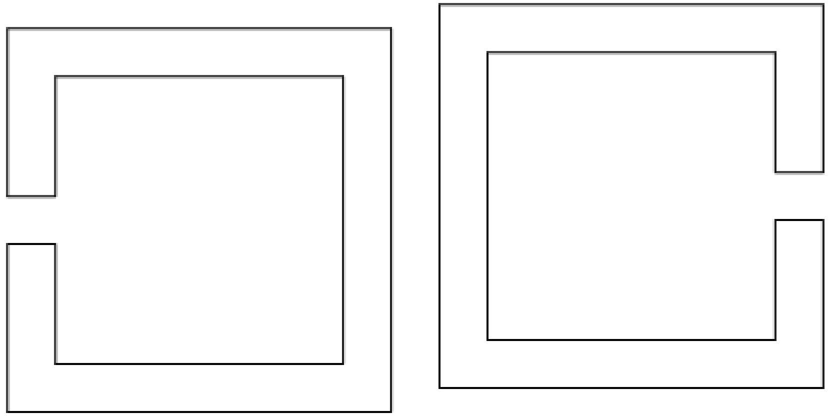

Fig. 9 Magnetic coupling of single-mode resonators [3].

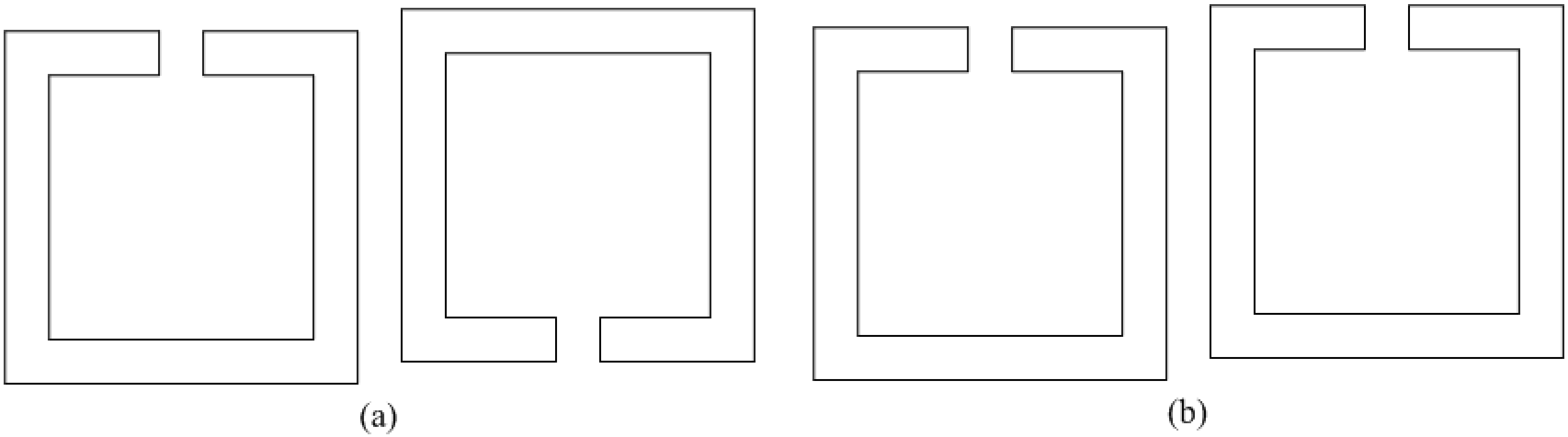

Fig. 10(a) & (b) Mixed coupling of single-mode resonators [3].

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Coupling coefficient

- The coupling coefficient (k) between two coupled resonators is defined as the ratio of coupled energy to stored energy.

$$k = \frac{\iiint \varepsilon \overline{E_1}.\overline{E_2} dv}{\sqrt{\iiint \varepsilon \left|\overline{E_1}\right|^2 dv * \iiint \varepsilon \left|\overline{E_2}\right|^2 dv}} + \frac{\iiint \mu \overline{H_1}.\overline{H_2} dv}{\sqrt{\iiint \mu \left|\overline{H_1}\right|^2 dv * \iiint \mu \left|\overline{H_2}\right|^2 dv}}$$

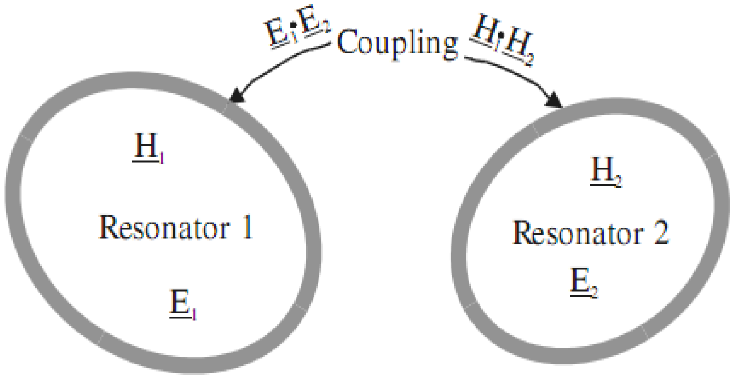


Fig. 11 General microwave coupled resonators [1].

- Direct evaluation requires the knowledge of field distributions and performance of space integrals which is not an easy task.
- So it may easier by using EM simulations to find characteristic frequencies that are associated with the coupling of resonators.

Electric coupling

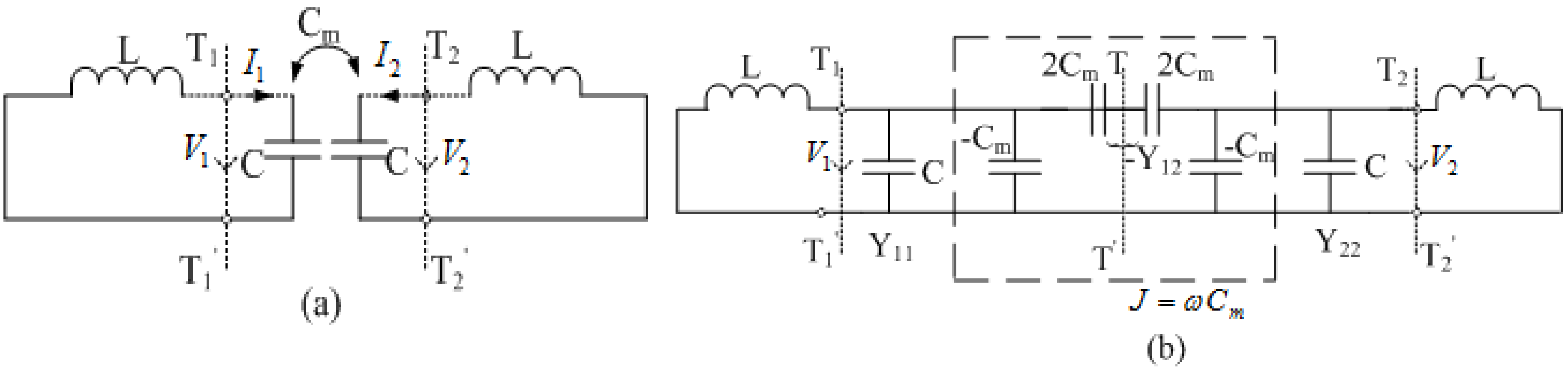


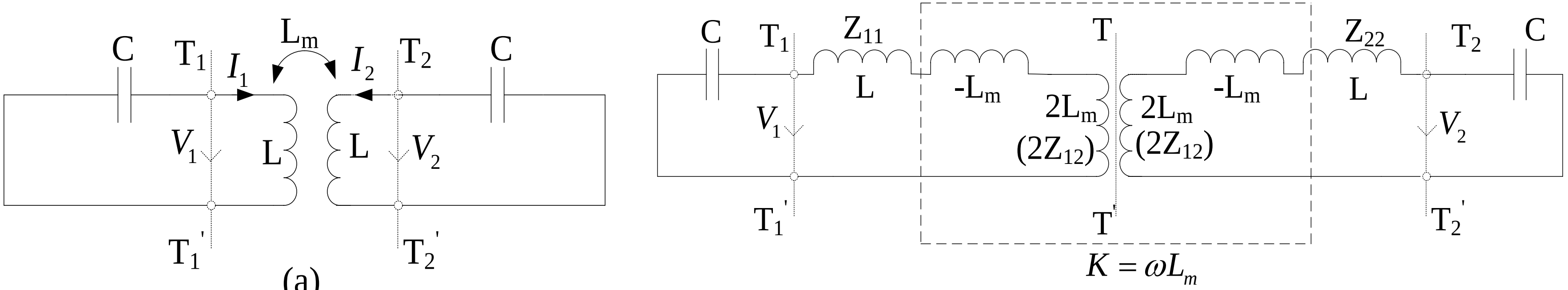
Fig. 12(a) Equivalent circuit of the coupled open-loop resonators exhibiting electric coupling. (b) An alternative form of the equivalent circuit with an admittance inverter $J = \omega C_m$

to represent the coupling [1].

$$f_e = \frac{1}{2\pi\sqrt{L(C+C_m)}} \qquad f_m = \frac{1}{2\pi\sqrt{L(C-C_m)}}$$

$$k_E = \frac{f_m^2 - f_e^2}{f_m^2 + f_e^2} = \frac{C_m}{C}$$

Magnetic coupling



(a) (b)

Fig. 13(a) Equivalent circuit of the coupled open-loop resonators exhibiting the magnetic coupling. (b) An alternative form of the equivalent circuit with an impedance inverter $K = \omega L_m$ to represent the coupling [1].

$$f_e = \frac{1}{2\pi\sqrt{(L - L_m)C}} \qquad f_m = \frac{1}{2\pi\sqrt{(L + L_m)C}}$$

$$k_M = \frac{f_e^{\,2} - f_m^{\,2}}{f_e^{\,2} + f_m^{\,2}} = \frac{L_m}{L}$$

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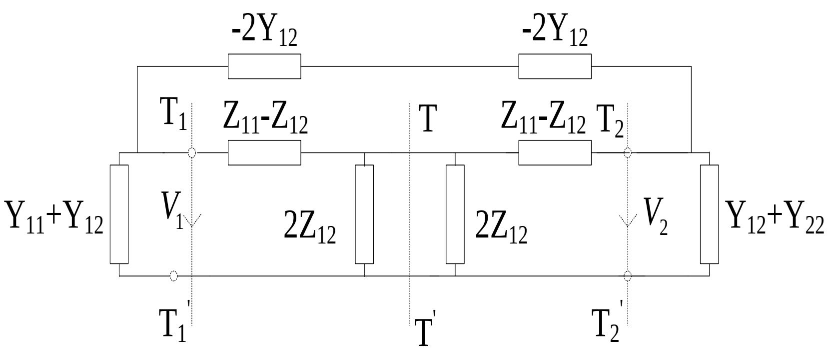
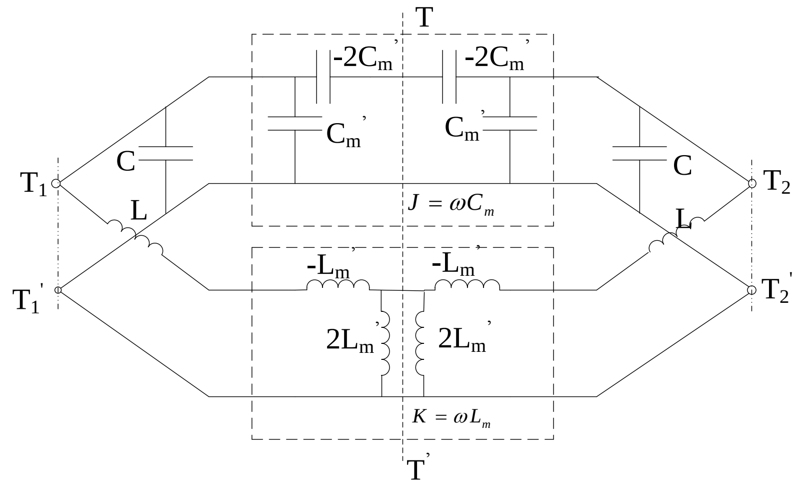
Mixed coupling



(a)



(b)

Fig. 14(a) Network representation of the coupled open-loop resonators exhibiting the mixed coupling. (b) An associated equivalent circuit with an impedance inverter $K = \omega L_m^{'}$ and an admittance inverter $J = \omega C_m^{'}$ to represent the magnetic coupling and electrical coupling respectively [1].

$$f_e = \frac{1}{2\pi\sqrt{(L - L_m^{'})(C - C_m^{'})}} \qquad f_m = \frac{1}{2\pi\sqrt{(L + L_m^{'})(C + C_m^{'})}}$$

$$k_B = \frac{f_e^2 - f_m^2}{f_e^2 + f_m^2} = \frac{CL_m^{'} + LC_m^{'}}{LC + L_m^{'}C_m^{'}} \qquad k_B \approx \frac{L_m^{'}}{L} + \frac{C_m^{'}}{C} = k_M^{'} + k_E^{'}$$

Dual mode microstrip open-loop resonator

- Each single-mode resonator is equal to an LC circuit, and produces a pole at the resonance frequency.
- But in order to design a filter with sharp rejection no of single-mode resonators are to be connected in cascade structures and this leads to increase in size of the filter.
- Each Dual mode resonator is a doubly tuned resonant circuit. So no of resonators for a given degree of filter is reduces by half.
- Here proposed design has the same size as single mode resonator with the help of ***loading element*** leads to compact in size.
- A loading element with a variable parameter ‘W’ is tapped from inside onto the open loop.

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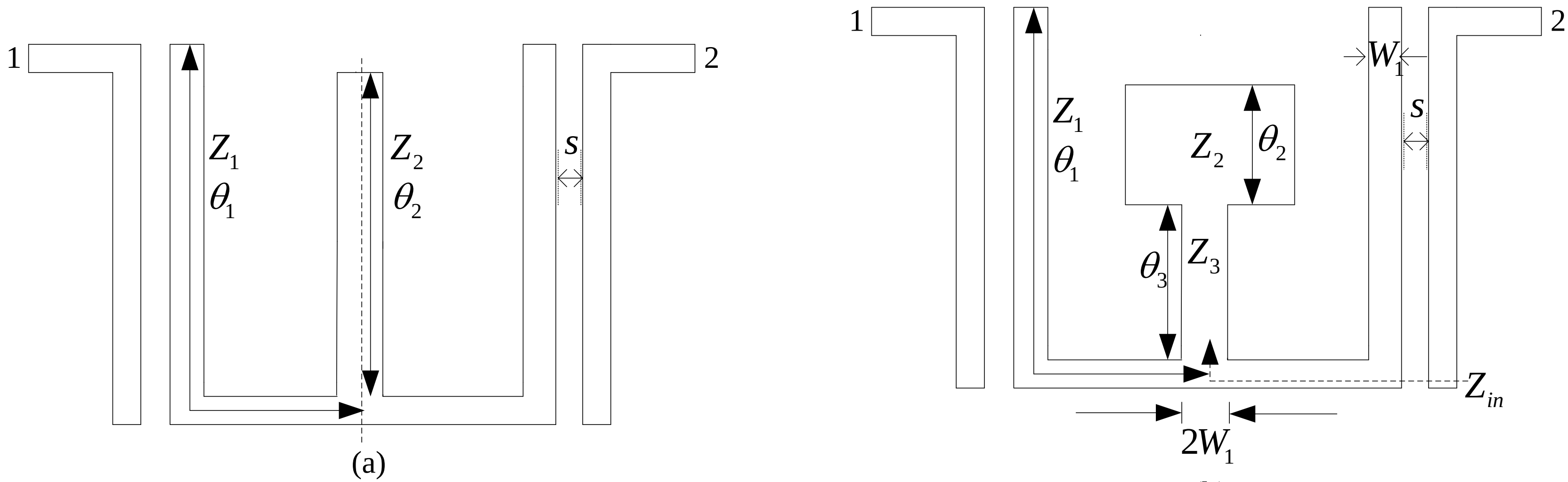
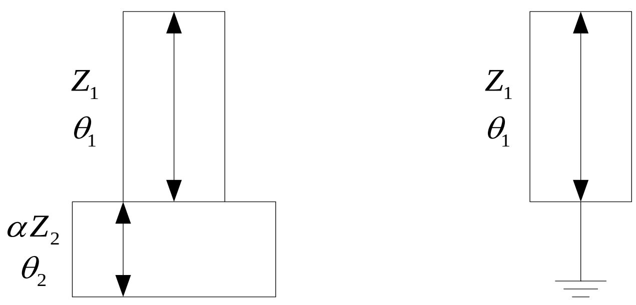


Fig. 15(a) Dual-mode resonator. (b) Stepped-impedance resonator (SIR).



$$\theta_1 \cong \frac{\pi}{2} \qquad \theta_2 \cong \pi - \frac{c}{4 f_{odd} \sqrt{\varepsilon_{eff}}}$$

$$\theta_2 = \cos^{-1}\left(\sqrt{\frac{R}{R+1}}\right) \qquad \theta_3 \cong (\pi + a\tan[-R\tan(\theta_2)]) - \left(\frac{c}{4 f_{odd} \sqrt{\varepsilon_{eff}}}\right)$$

Fig. 16(a) Even mode resonator. (b) Odd mode resonator.

Characteristics

Change of width of loading element 'W' leads to mode splitting.

Two modes exists

1. Odd mode
2. Even mode

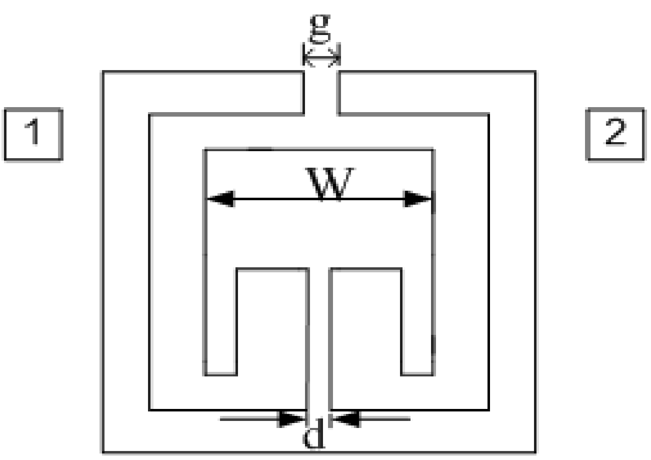


Fig. 17 Dual mode resonator[2].

1. The resonance frequency which is not affected by change of width of loading element is called odd-mode.
2. The resonance frequency which is affected by change of width of loading element is called even-mode.

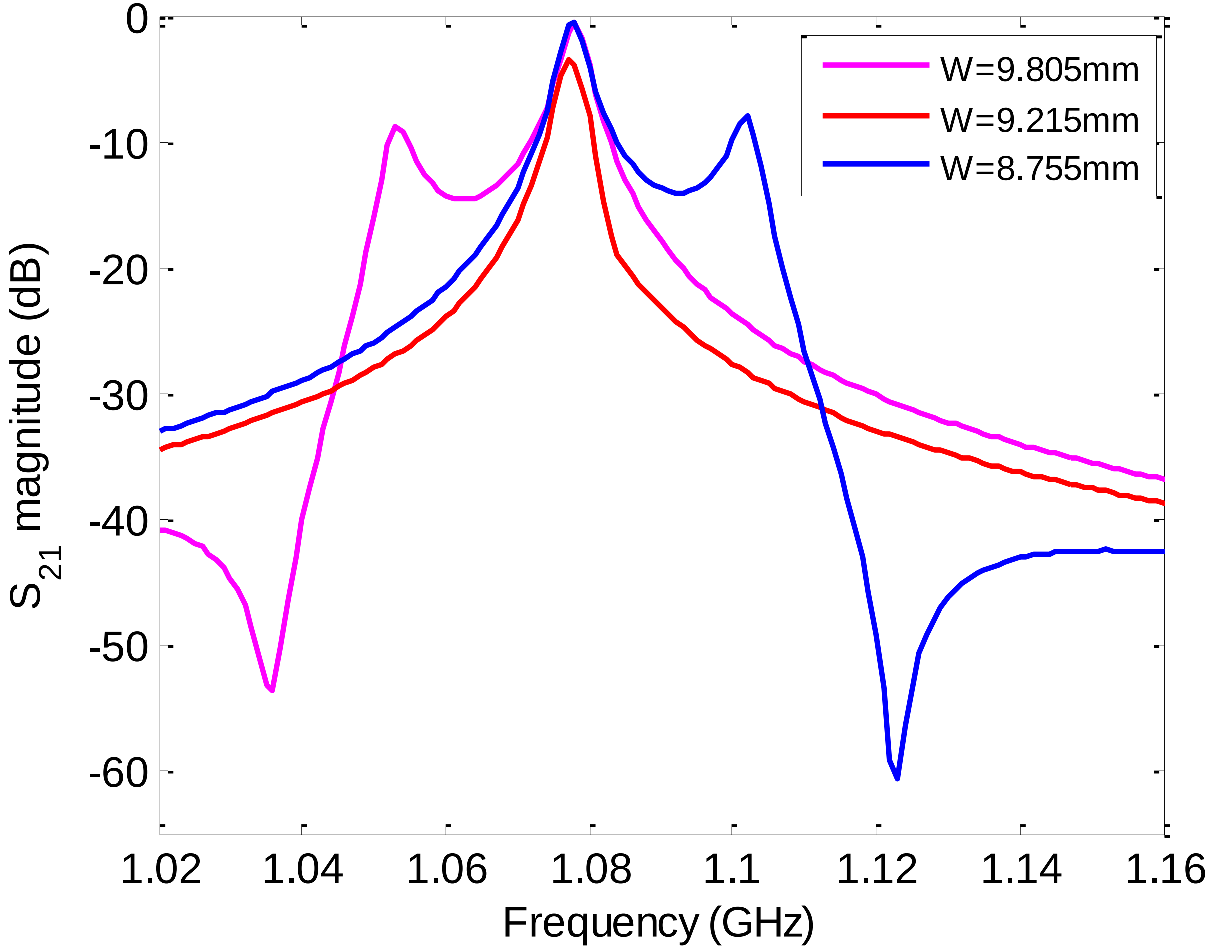


Fig. 18 Modal-resonant characteristics of the proposed dual-mode microstrip open-loop resonator for g=0.9mm and d=1.1mm.

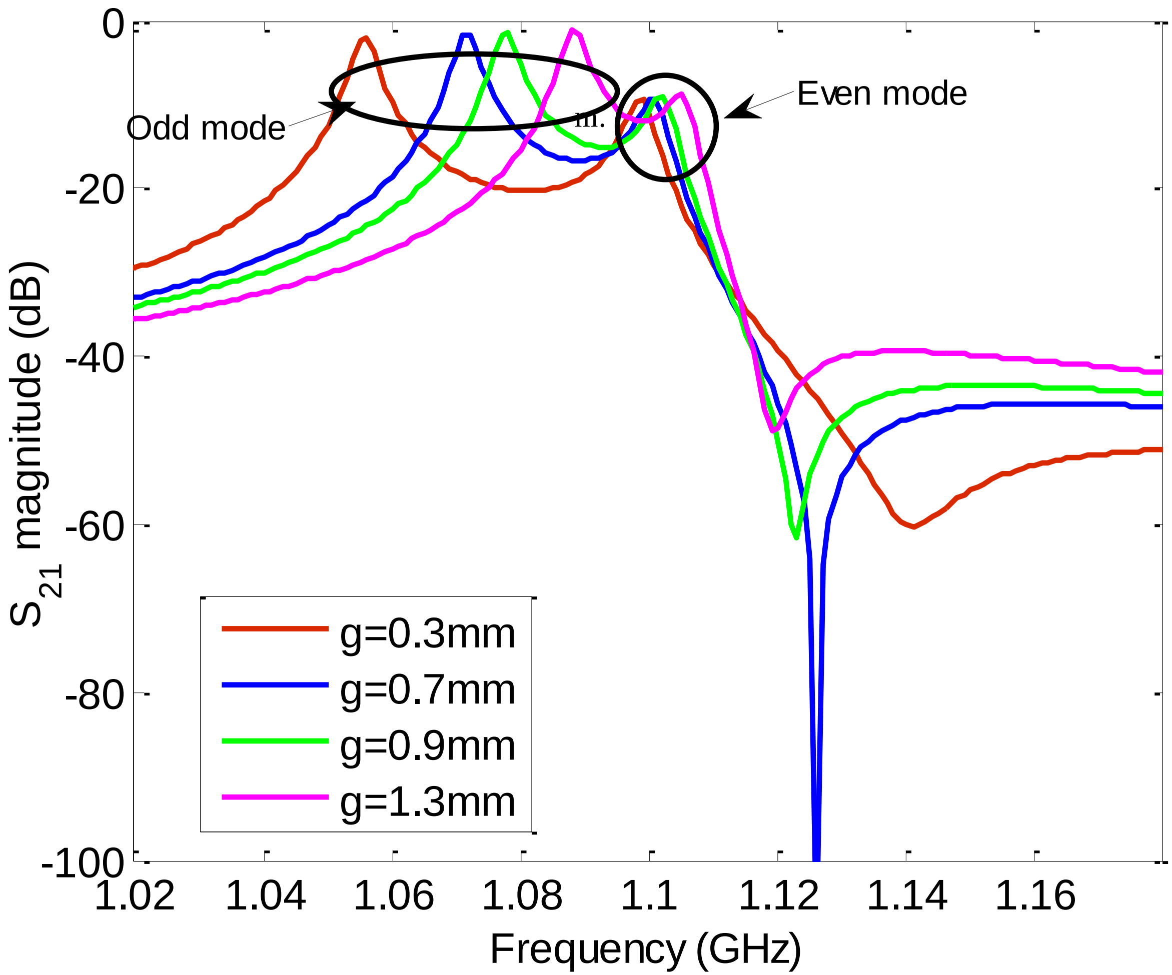


Fig. 19 g-dependence of modal resonant characteristics of the proposed dual-mode microstrip open-loop resonator for W=8.755mm and d=1.1mm.

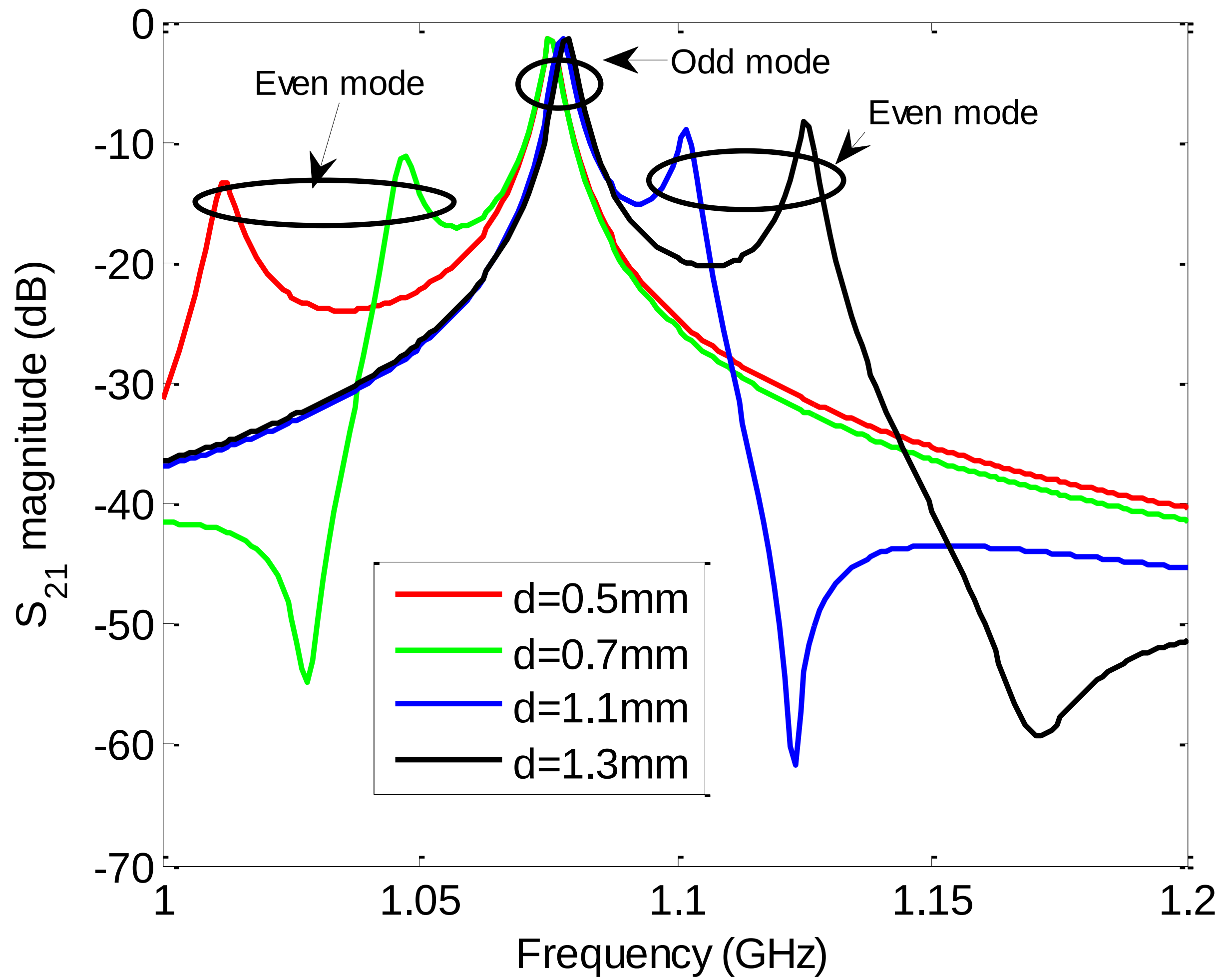


Fig. 20 d-dependence of modal resonant characteristics of the proposed dual-mode microstrip open-loop resonator for W=8.755mm and g=0.9mm.

Contd…

- To excite the resonator , weakly coupled ports are used, for a single value of ‘W’ the two modes exhibits same resonance frequency. as ‘W’ increases/decreases, the two modes split.

- Smaller ‘W’, shifts resonance frequency of even mode to right and larger ‘W’, shifts resonance frequency of even mode to left.

- Due to short circuit at tapped point no charge or current in the odd mode case in the loading element, and maximum current in the even mode case in loading element.

- There is a finite frequency transmission zero as the modes split.

- Transmission zero is on right side if even mode frequency is more than odd mode frequency and on left side if odd mode frequency is more than even mode frequency.

Properties of dual-mode resonator

- The transmission zero is related to the even mode case only.

- There are 2 properties of dual-mode resonator.
  1. It exhibits a transmission zero for filter design of asymmetric response.
  2. Two modes are not coupled to each other even after they split.

- From the theory of asynchronous tuned coupled resonator, two split mode frequencies are equal to two self resonant frequencies and no coupling between these two resonators.

- To find these separate frequencies response place a magnetic/electric wall along the line of symmetry leads to two self resonant frequencies.

- To design a filter one need to allocate the modal frequencies in the passband.

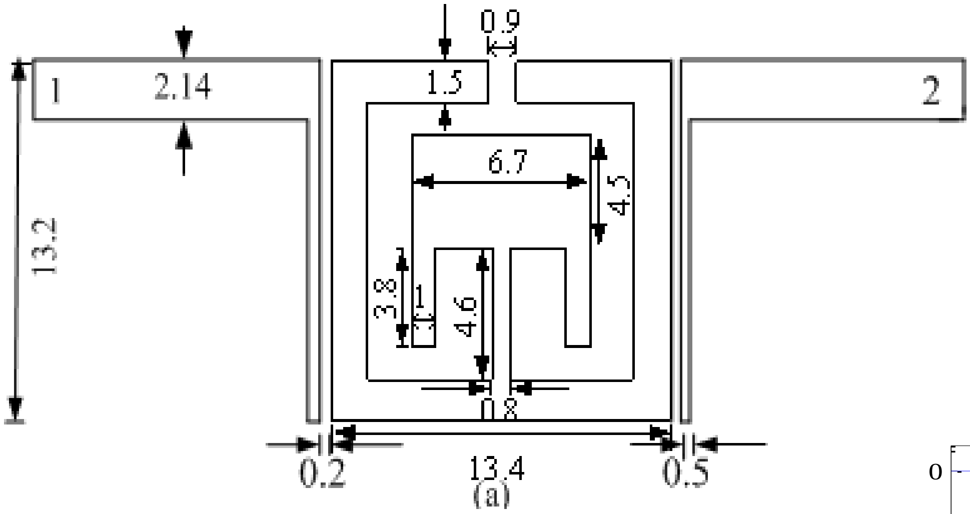
Design Procedure

- For the given substrate find the guided wavelength using center frequency of the required filter.
- Here side of square open-loop resonator is one eighth of guided wavelength.
- Then adjust the gap such that it odd mode resonance frequency is equal to the given center frequency.
- Using ‘W’ and ‘d’ place the even mode resonance frequency in the passband so as the transmission zero is in the stopband.
- Place no of sections to get sharp roll-off and give the coupled-line coupling for the ports instead of tapered line coupling.

NRN Coupling Element

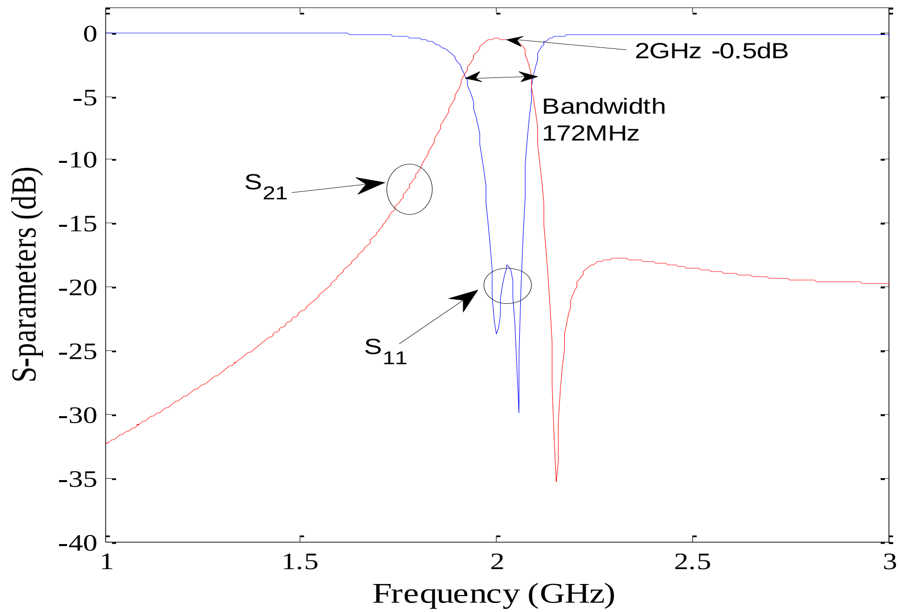
- The two dual-mode resonators without any direct coupling between them are cascaded through the two non resonating nodes, as shown in the diagrams.
- The advantage of this method is we can vary the parameters of the each dual-mode resonator independently.
- Generally this method is used for the symmetric frequency response to get at the both sides of the passband.

Bandpass filter using Dual-mode open-loop resonator



The resonant frequency of the proposed design is 2 GHz, quality factor is 11.6 and bandwidth is 172MHz.

Fig. 21 Dual mode open-loop filters [2]. (a) Simulation diagram showing week I/O coupling to the resonator (all units are in mm).
(b) Frequency response using Zeland [4].



Quad-Section Mixed Coupling using NRN Coupling Elements (on TMM10 substrate)

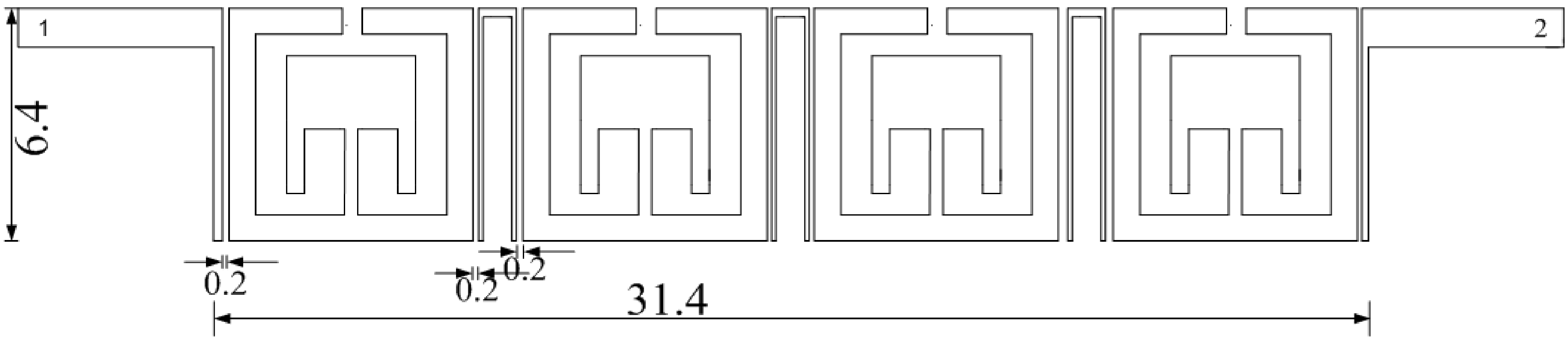


Fig. 22(a) Quad-section using NRN coupling element (all dimensions are in mm).

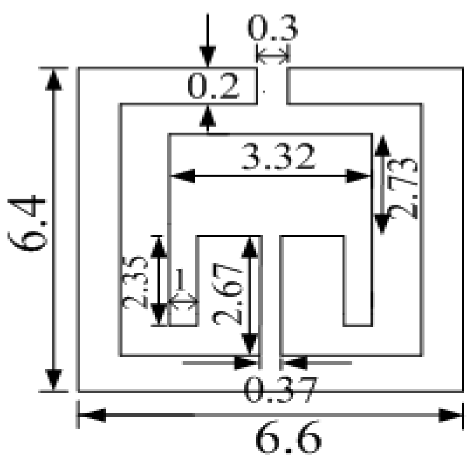


Fig. 22(b) Single unit dimensions (all dimensions are in mm).

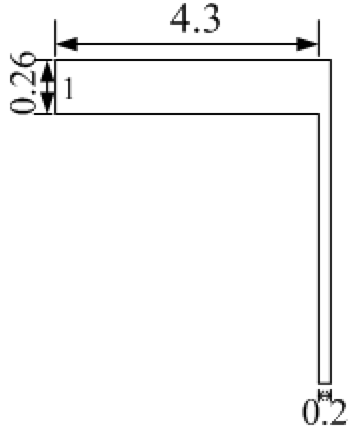


Fig. 22(c) Port Dimensions (in mm).

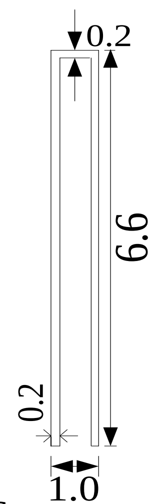


Fig. 22(d) NRN(all dimensions are in mm).

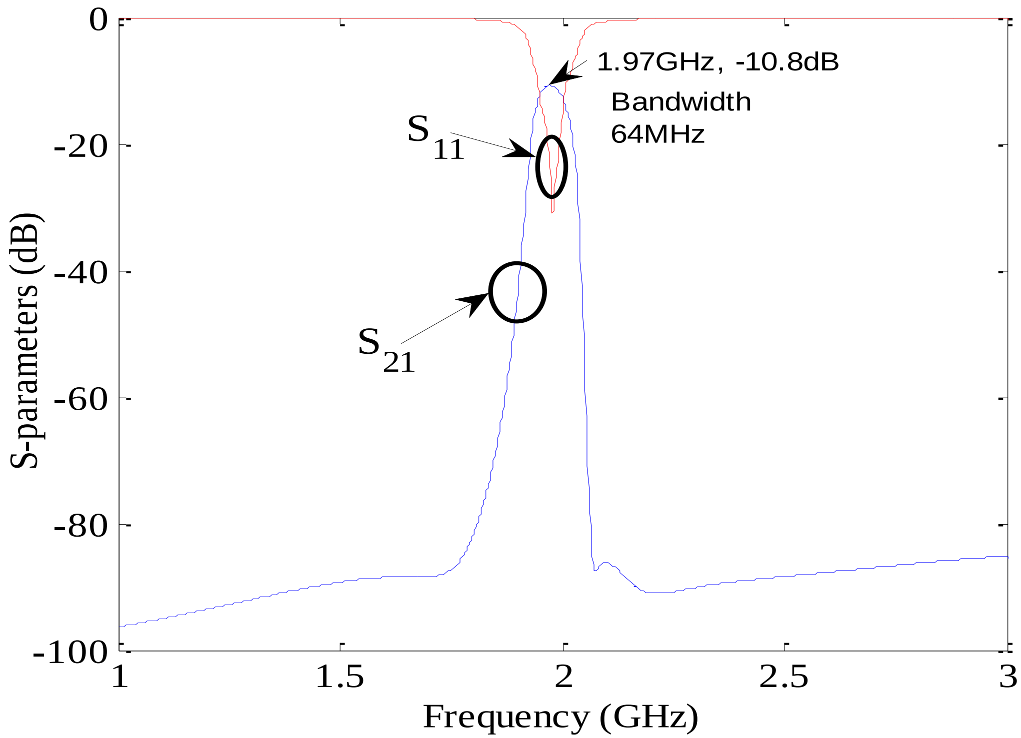


Fig. 23 S-parameters of the Quad-section using NRN coupling element.

Results

- Insertion loss in pass band at 1.97GHz is 10.8dB,
- Here 87dB isolation is achieved between 1.97GHz and 2.08GHz.
- The filter roll-off rate = 790dB/GHz on the upper side of the pass band.
- The return loss in pass band is better than 18 dB.
- The upper band rejection is better than 80 dB from 2.08GHz to 3 GHz.
- The over-all quad-section size is $0.81\lambda g \times 0.13\lambda g$.

Quad-Section Mixed Coupling using NRN Coupling Elements (on Woven TFG substrate)

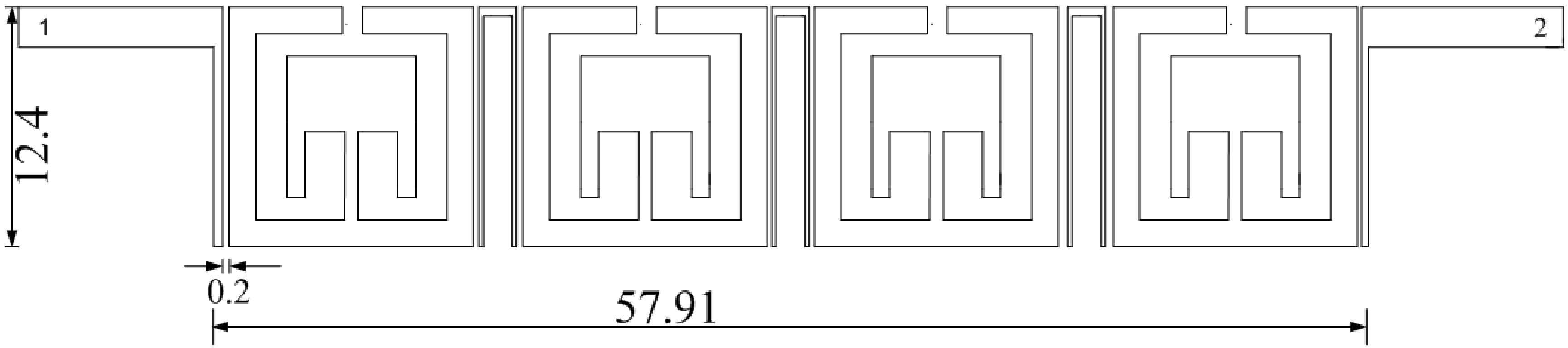


Fig. 24(a) Quad-section using NRN coupling element (all dimensions are in mm).

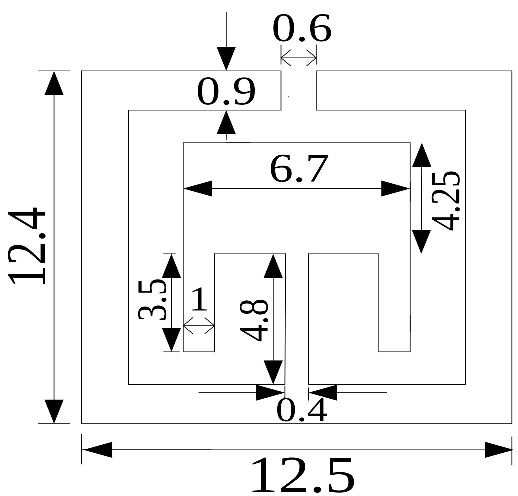


Fig. 24(b) Single unit dimensions (all dimensions are in mm).

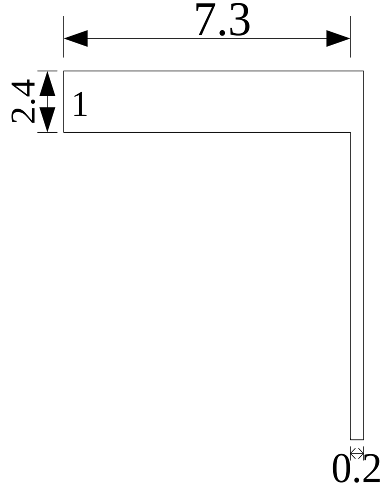


Fig. 24(c) Port Dimensions (in mm).

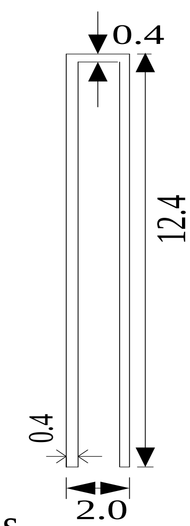


Fig. 24(d) NRN (first and third NR are equal length of 2 mm, second NRN is 1.91mm length) (all dimensions are in mm).

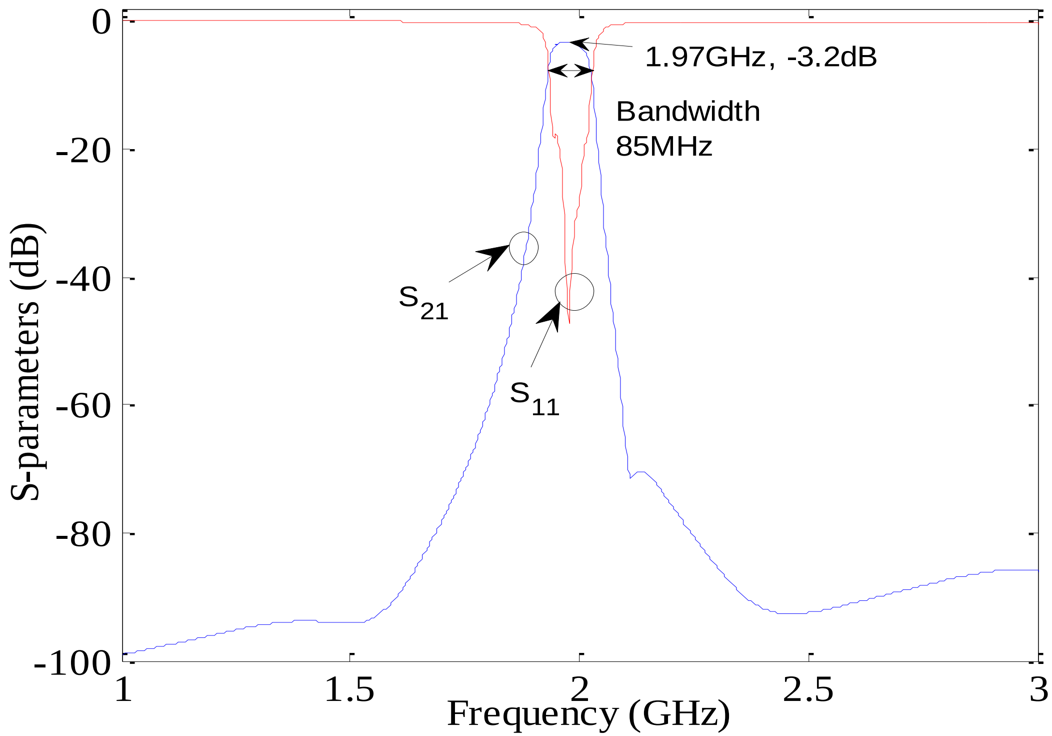


Fig. 25 S-parameters of the Quad-section using NRN coupling element.

Results

- Insertion loss in pass band at 1.97GHz is 3.2dB.
- Here 70dB isolation is achieved between 2.0GHz and 2.11GHz.
- The filter roll-off rate = 636 dB/GHz on the upper side of the pass band.
- The return loss in pass band is better than 18 dB.
- The upper band rejection is better than 70 dB from 2.11to 3 GHz.
- The over-all quad-section size is $0.77\lambda g \times 0.14\lambda g$.

Quad-Section Direct Mixed Coupling without using NRN Coupling Elements (on Woven TFG substrate)

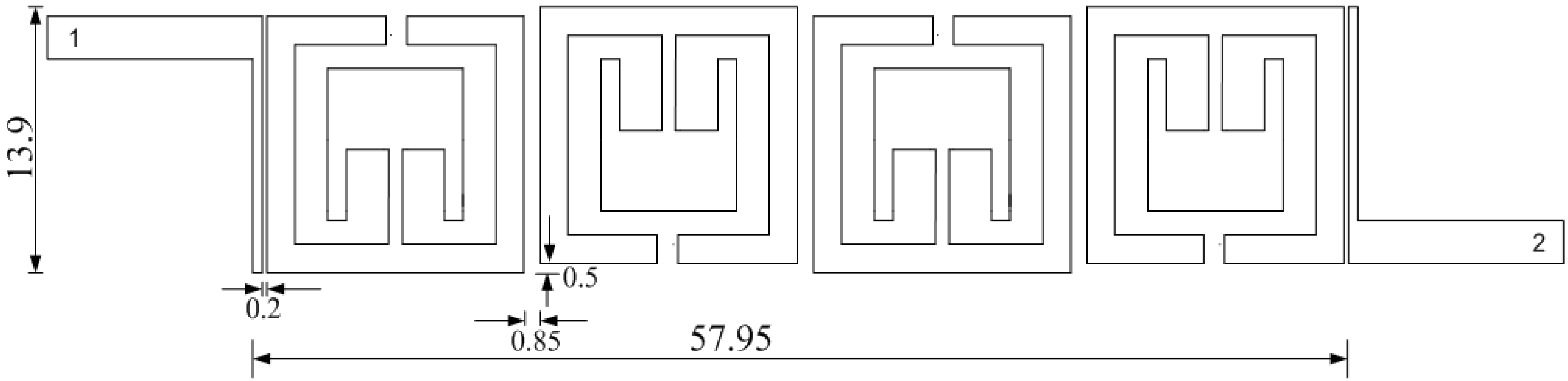


Fig. 26(a) Quad-section using NRN coupling element (all dimensions are in mm).

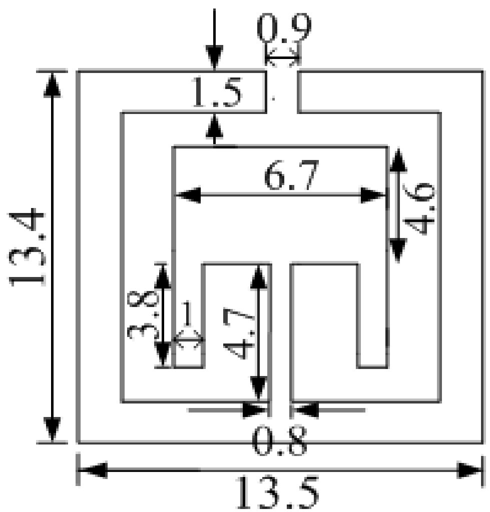


Fig. 26(b) Single unit dimensions (all dimensions are in mm).

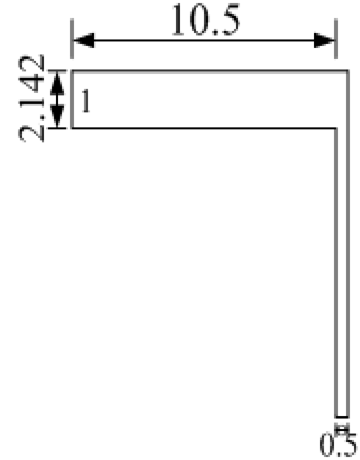
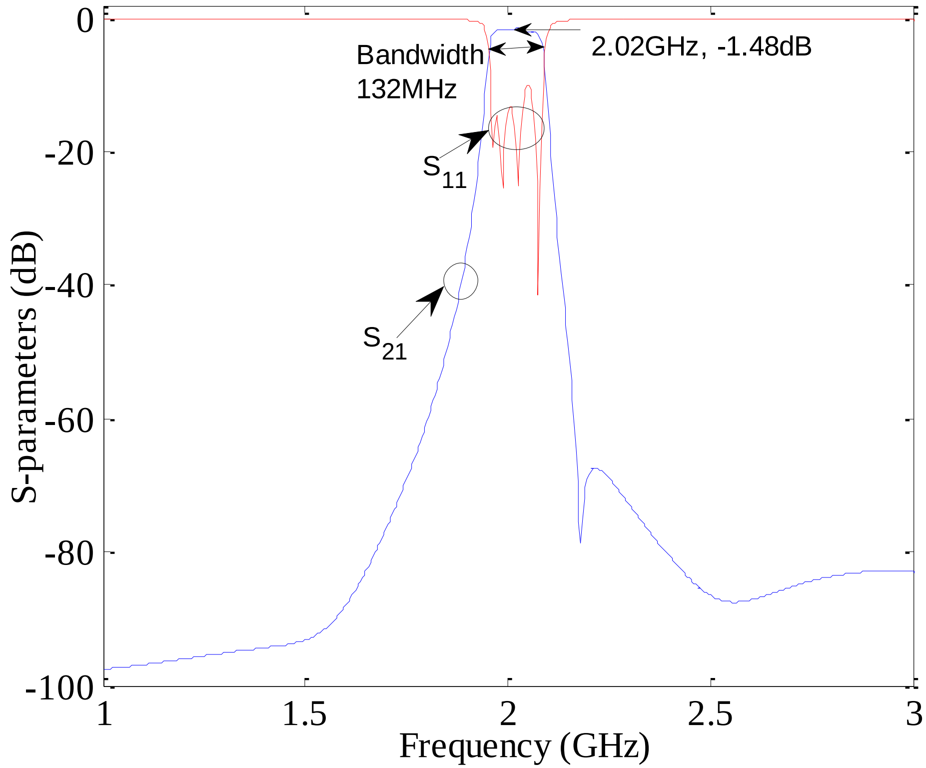


Fig. 26(c) Port Dimensions (in mm).



Results

Fig. 27 S-parameters of the Quad-section direct mixed coupling.

- Insertion loss in pass band at 2.02GHz is 1.48dB and at 2.18GHz is 78.51dB.
- The filter roll-off rate = 760 dB/GHz on the upper side of the pass band.
- 76dB isolation is achieved between 2.08GHz and 2.18GHz.
- The return loss in pass band is better than 10 dB.
- The upper band rejection is better than 70 dB from 2.2 GHz to 3 GHz.
- The over-all quad-section size is $0.61\lambda g \times 0.14\lambda g$.

Conclusions

- The miniaturization of microwave filters at lower frequencies.
- One of the most popular structures for microstrip implementations is the square open loop resonator due to its compact size and versatility.
- Here design of narrowband bandpass filter using dual-mode open-loop resonators is studied and design procedure includes the ease of fabrication, high performance.

Results

- Insertion loss in pass band at 2.02GHz is 1.48dB and at 2.18GHz is 78.51dB.
- The filter roll-off rate = 760 dB/GHz on the upper side of the pass band.
- 76dB isolation is achieved between 2.08GHz and 2.18GHz.
- The return loss in pass band is better than 10 dB.
- Upper band rejection of insertion loss better than 70 dB from 2.2GHz to 3GHz.
- The over-all quad-section size is $0.61\lambda g \times 0.14\lambda g$.

Future work

- Verify the simulated results with measured data.
- Any another structure leads to compact size and produce improved insertion loss in pass-band for the given design problem.
- The design can be extended to fractal structure so that size will be further reduced.
- The work can be extended to different substrates with proper design of the resonator.
- Multi layer design can also be possible.

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