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MINIATURIZATION OF THE BANDPASS MICROWAVE FILTER BASED ON SPIRAL METAMATERIAL RESONATORS

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Abstract

The purpose of this article is the miniaturization of a microwave passband filter. The miniaturized filter is a capacitive gap filter coupled in series by their ends. Our miniaturization procedure is based on the combination of the bandpass filter with periodic metamaterial resonators of spiral shape with negative permeability (μ<0). We will maintain nine (SRRs) of the same dimensions vertically to the capacitive gaps of the primary filter to control the resonance frequency of the overall structure. The dielectric substrate chosen for the etching of the capacitive resonators of the primary filter and metamaterial resonators (SRRs) is the Rogers RO 4003™ which has the dielectric constant (ε_r = 3.55) and the loss tangent (tanδ = 0.0027). Since there are no scientific or experimental results in the scientific literature for this type of complicated structure, we had to make simulations using the software CST Microwave Studio.

Keywords:

Band-Pass Filter, Capacitive Gaps, CST Microwave Studio, Metamaterials, Permeability, Permittivity, SRRs

1. INTRODUCTION

Currently, one of the most desired goals for the wireless communications system industry is to improve the performance of microwave filters, such as bandpass filters that this type of filter is commonly used in devices of modern telecommunication. The filter performance is a major challenge in the RF or Microwave field, improving the electrical qualities of the filters is the main objective of the studies. The choice of the material constituting the filter elements is an important factor to achieve the desired performance. A new class of materials for producing microwave filters shows a big difference compared to conventional materials in terms of the physical and geometrical characteristics of filters, these devices are called metamaterials.

Metamaterials are a special class of structured artificial materials that exhibit new electromagnetic properties that do not exist in nature. In 1968, an analysis of this kind of material was originally made by the Russian physicist Victor Veselago [1], he proposed that metamaterials have different properties compared to conventional media, including negative refraction [2], a Cerenkov radiation inversion [3] and the Doppler Effect [4]. These properties can divide into two large classes, physical and geometric. The physical properties of metamaterials such as the nature of the permeability (μ) and permittivity (ε) [5, 6] and the geometric properties such as the size of the resonators [7] represent an essential tool for the study of new filtering structure in microwave. Today, the new metamaterial devices are used for better performance and reliability for modern telecommunication systems (antennas, filters, couplers), among these devices there in the split ring resonators metamaterials (SRRs) which have a magnetic resonance [8], [9].

To show the influence of metamaterial resonators on the quality of microwave filters, we propose in this paper a new structure that includes a filter with capacitive gaps coupled in series by their ends, this filter is associated with (SRRs) spiral forms. A suitable choice of the dimensions of (SRRs) and their positions relative to the primary filter allows us to obtain the miniaturization of our global filter.

2. METHODOLOGY

2.1 SYNTHESIS OF THE MICROWAVE FILTER WITH CAPACITIVE CAPACITOR GAPS IN SERIES

The microwave filter with capacitive gaps connected in series is a filter that uses microstrip resonators coupled in series via their ends, each resonator has a half-wavelength ($\lambda/2$) at the center frequency (f_0) of the bandwidth of this filter. In this kind of filter, we use the impedance or admittance inverters (J_i, i+1) which allow maximum levels of thinking towards the end of impedances each half-wave microstrip resonator. Capacitive gaps function as purely capacitors in series. The synthesis of such a filter is obtained by using the standardized low-pass prototype according to the Tchebyshev filtering function and the number of microstrip resonators constituting the filter to be studied. The Matthaei synthesis [10] used in this article for the filter shown in Fig.1, can be summarized as follows.

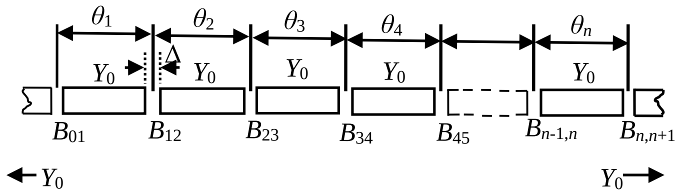

Fig.1. Capacitive gap filter coupled in series

- The elements (g_i) of the low-pass prototype according to the Tchebyshev filter function are:

$$\begin{cases} g_0 = 1 & g_1 = \dfrac{2a_1}{\gamma} \\ g_i = \dfrac{4a_{i-1}a_i}{b_{i-1}b_i} & for\ i = 2,...,n \end{cases} \quad (1)$$

$$\begin{cases} g_{n+1} = 1; & n \text{ is odd} \\ g_{n+1} = \tan^2\left(\frac{\beta}{4}\right); & n \text{ is even} \end{cases} \quad (2)$$

$$\begin{cases} a_i = \sin\left[\frac{(2i-1)\pi}{2n}\right]; & for\ i = 1,2,\dots,n \\ b_i = \gamma^2 + \sin^2\left[\frac{i\pi}{2n}\right]; & for\ i = 1,2,\dots,n \end{cases} \quad (3)$$

where: $\gamma = \sin\left[\frac{\beta}{2n}\right]$ and $\beta = \ln\left(\coth\left(\frac{r_p}{17.37}\right)\right)$

- The Inverter parameters are:

$$\begin{cases} \frac{J_{0,1}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{\delta}{g_0 g_1 \omega_1'}} \\ \frac{J_{i,i+1}}{Y_0} = \frac{\pi\delta}{2\omega_1'}\frac{1}{\sqrt{g_i g_{i+1}}} & for\ i = 1,2,\dots,n-1 \\ \frac{J_{n,n+1}}{Y_0} = \sqrt{\frac{\pi}{2}\frac{\delta}{g_n g_{n+1}\omega_1'}} \end{cases} \quad (4)$$

With:

ω_1' represents the normalized cut-off frequency at -3dB of the low-pass prototype.

$\delta = (f_2-f_1)/f_0$ is the relative bandwidth of the filter after frequency transformations.

Y_0 represents the admittance of the input and output lines ($Y_0 = 1/Z_0$)

- The susceptances of capacitive coupling in series are:

$$\frac{B_{i,i+1}}{Y_0} = \frac{\frac{J_{i,i+1}}{Y_0}}{1-\left(\frac{J_{i,i+1}}{Y_0}\right)^2} \quad for\ i = 1,2,\dots,n-1 \quad (5)$$

- The electrical distances of the capacitive gaps are:

$$\theta_i = \pi - 0.5\left[\tan^{-1}\left(\frac{2B_{i-1,i}}{Y_0}\right) + \tan^{-1}\left(\frac{2B_{i,i+1}}{Y_0}\right)\right]$$

radians, for : $i = 1, 2, \dots, n$. (6)

2.2 SPIRAL (SRR) ANALYSIS

The Fig.2 shows the spiral shape of (SRR), it is a structure which has been proposed for the first time by Baena [11]. The metamaterial spiral resonator (SRR) is a resonator derived from the classical resonator discovered by Pendry [12]. In the (SRR) spiral, the two outer and inner rings are connected to each other in a continuous manner. The resonance frequency of (SRR) spiral is smaller than that of conventional (SRR); these frequencies are connected by the following relationship.

$$f_r\,(\text{spiral SRR}) = 0.5 f_r(\text{conventional SRR}) \quad (7)$$

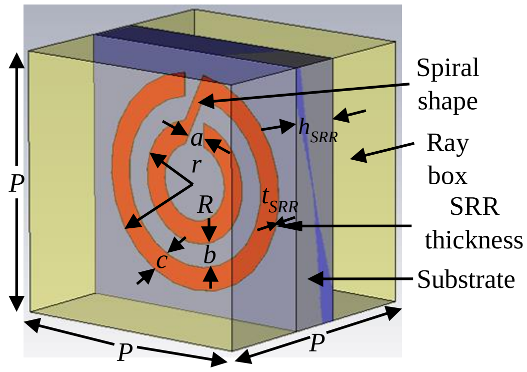

Fig.2. (SRR) spiral in 3-D

The (SRR) can be characterized by the following physical and geometrical parameters.

- The geometric parameters:
  - P = period of the structure,
  - a = width of cuts of the rings.
  - b = spacing between the two rings,
  - c = width of both rings.
  - R = outer radius of the large ring,
  - r = outer radius of the small ring of the spiral (SRR).
  - h_{SRR} = Substrate thickness,
  - t_{SRR} = thickness of the rings engraved on the substrate.
- The physical parameters of the (SRR) are:
  - ε_r = relative permittivity of the substrate.

Conductive tracks which form the two rings are on copper.

3. SIMULATION RESULT IN CST MICROWAVE STUDIO

3.1 SIMULATION OF THE TCHEBYSHEV PRIMARY FILTER

On a substrate of the Rogers RO 4003™ ($\varepsilon_r = 3.55$) which has loss factor ($\tan\delta = 0.0027$) and thickness ($h = 1.54$mm), the design of the gap filter according to the Tchebyshev filtering function is made using the seven ($n = 7$) microstrip resonators, each one has the thickness which is (t). The filter dimensions are obtained to have a center frequency around 21.5GHz, the width (W) of the input and output lines are selected to obtain an adaptation to (Z_0 = 50Ω) and the ripple in the bandwidth is (r_p = 0.2dB). Our design is based on the requirement: $W/h = 1.2$ and ($t = 5$µm $\ll h$).

The input and output lines have the same length ($l_{in} = l_{out}$ = 7.1325mm).

- Applying the synthesis Matthaei and also the chart designating the widths of gaps between the microstrip resonators (Δ as a function of the central frequency f_0), we can summarize the geometric characteristics of this filter from Table.1.

Table.1. Geometric characteristics of the capacitive gap filter

i	g_i	$J_{i,i+1}/Y_0$	$B_{i,i+1}/Y_0$	θ_i (rd)	I_i (mm)	$\Delta_{i,i+1}$ (mm)
0	1.0000	0.2870	0.3127			0.0520
1	1.3723	0.0811	0.0800	2.7813	2.6568	0.0940
2	1.3782	0.0638	0.0640	2.9970	2.8632	0.1800
3	2.2757	0.0611	0.0613	3.0153	2.8800	0.1890
4	1.5001	0.0611	0.0613	3.0180	2.8830	0.1890
5	2.2757	0.0638	0.0640	3.0153	2.8800	0.1800
6	1.3782	0.0811	0.0800	2.9970	2.8632	0.0940
7	1.3723	0.2870	0.3127	2.7813	2.6568	0.0520

So, the microwave filter then has seven microstrip resonators coupled in series of electrical lengths (θ_i), with eight capacitive gaps of width ($\Delta_{i,i+1}$).

- The substrate of this filter has dimensions ($m \times q \times h$) with:

  m = 34mm (total length of the substrate).

  q = 12mm (substrate width).

  h = 1.54mm (substrate thickness).

  W = 1.848mm (width of both input and output lines and also microstrip resonators).

- The Fig.3 shows the final shape of the filter simulated in CST Microwave Studio.

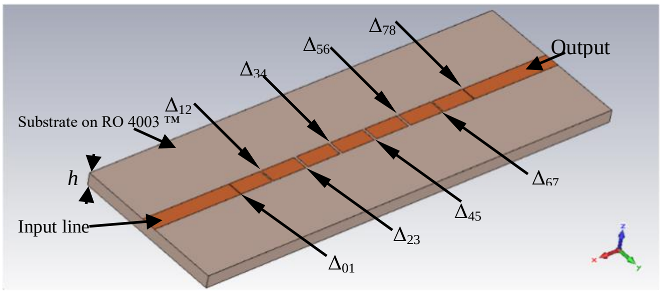

Fig.3. Tchebyshev filter with seven coupled microstrip resonators

After having simulated the filter represented in Fig.3, the frequency response can be visualized by the following figure.

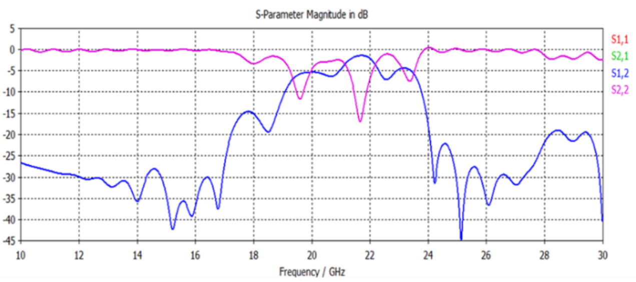

Fig.4. [S] Parameters of primary filter

The Fig.4 provides in the frequency range (10-30)GHz, the frequency response of the Tchebyshev filter which has seven capacitive coupled microstrip resonators. This figure shows a bandpass behavior of the filter for the central frequency of the order of (f_0 = 21.5GHz). This is a filter that resonates at a very high frequency with a wide bandwidth because of the electromagnetic coupling generated by the microstrip resonators between them is important which is justified by the small widths ($\Delta_{i,i+1}$).

3.2 ELECTROMAGNETIC BEHAVIOR OF SPIRAL (SRR)

The spiral split ring resonator (SRR) chosen for the combination with the capacitive gap filter is sized to have a much lower resonant frequency than the resonant frequency of the primary filter.

- The (SRR) parameters are: P = 3mm, $a = b = c$ = 0.2mm, R = 1.3mm, r = 0.9mm. Rogers Substrate RO 4003 ™ (ε_r = 3.55) for the thickness (h_{SSR} = 1.54mm). The thickness of copper rings ($t_{SSR} = t$ = 5µm).

The simulation of (SRR) is done in CST Microwave Studio, using a ray box of the same period (P = 3mm) to minimize insertion losses.

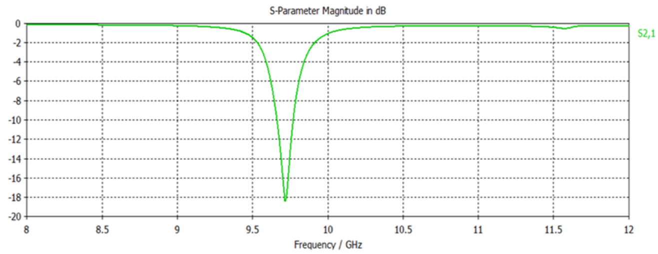

Fig.5. Coefficient of transmission of spiral (SRR)

The Fig.5 provides in the frequency range (8-12)GHz, the simulation results of (SRR), it shows a transmission coefficient band-stop behavior (S_{21}), which has a minimum of -18dB at resonant frequency f_r = 9.70GHz which is much lower than the resonance frequency of the bandpass primary filter.

3.3 SIMULATION OF THE OVERALL FILTER

The overall structure consists of the bandpass filter with series coupled microstrip resonators with capacitive gaps and spiral (SRRs), the position of (SRRs) and their dimensions make it possible to control the resonance of the bandpass filter alone. Tchebyshev bandpass filter has attenuation outside the (18-24)GHz frequency band, and then around the resonance of (SRRs) there is no propagation so we have evanescent waves.

- The dimensions of (SRRs) are the same as those of (SRR) shown in Fig.2.
- The total length of the Tchebyshev capacitive gap filter allows us to choose the number (N = 10) of the (SRRs) that must be used to have a feeding of these (SRRs) from the input and output lines of the filter.
- The Fig.6 shows the overall structure of the filter composed by microstrip resonators and spiral (SRRs).
- The Fig.7 shows the ideal position of (SRRs) to the Tchebyshev filter; it justifies the choice of the number of (SRR) for association with microstrip resonators.
- In CST Microwave Studio, we feed the global filter by two ports which have dimension Δ and σ, where ($5h \leq \Delta \leq 10h$) et ($0 \leq \sigma \leq 6$h). The (SRRs) are vertically coupled to the microstrip resonator for a good electromagnetic coupling.

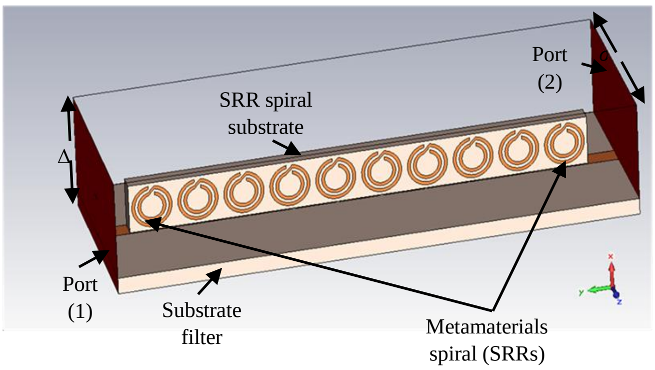

Fig.6. Association of the Tchebyshev filter and the spiral (SRR)

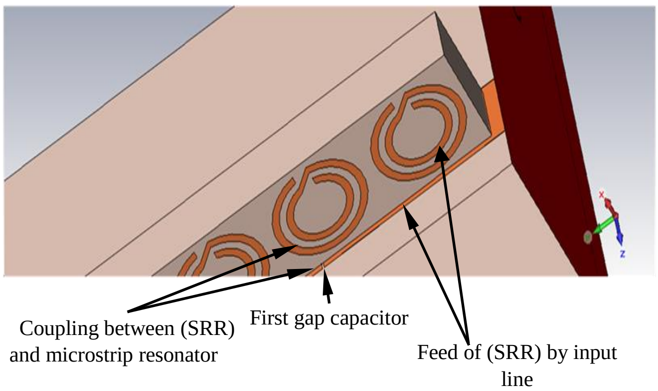

Fig.7. Feeding and coupling (SRRs)

After simulation, we can get the response of the overall filter that is represented by the Fig.8.

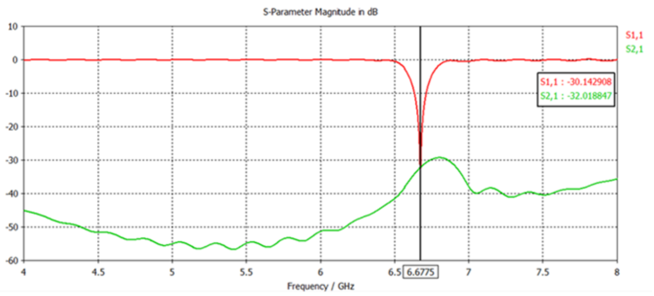

Fig.8. [S] Parameters of the global filter

The Fig.8 shows that the behavior of the global filter composed by the coupled microstrip resonators and the spiral (SRRs) is a bandpass. Our global filter has a resonance around the approximate center frequency f_0' = 6.67GHz instead of 21.5GHz. So, it can be noticed that by the using of metamaterial resonators we obtained a bandpass filter of central frequency in the C band which requires considerable dimensions. It must be said that in our design we have modest dimensions which justifies the miniaturization of the overall filter.

4. CONCLUSIONS

A new microwave filtering structure is proposed in this work, the behavior of the sought filter was a bandpass. The miniaturization of the Tchebyshev filter with capacitive gaps is obtained by using of metamaterial resonators. To have the desired miniaturization, we used spiral ring split resonators (SRRs) to minimize the center frequency of the overall filter. In a vertical way, we placed the ten (SRRs) above the seven microstrip resonators constituting the primary filter to be miniaturized in order to have the electromagnetic coupling necessary so as not to disturb the bandwidth of the global filter. Our simulation results have shown that using metamaterials, we can obtain a filter that operates in the frequency band C based on modest dimensions, which justifies our work for the miniaturization of the microwave filter.

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