Security
of Infocommunication Systems
and Internet of Things

2023 Vol 1, No 1

https://doi.org/10.31861/sisiot2023.1.01001

Received 20 March 2023; revised 17 May 2023; accepted 05 June 2023; published 30 June 2023

Ring Resonators-Based Adjustable Bandpass Filter for Microwave Application

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ABSTRACT The paper presents the principle of a microwave adaptive band-pass filter based on the cascade of ring resonators. The filter is performed as a planar microstrip technology with thickness of around 1 mm to ensure compactness of the device. The ring resonators, being a part of metamaterials, can be considered as an equivalence of an oscillator and is conventionally used in the microwaves. While a quite number of the filters with predefined parameters are well-known, the adaptive filters the throughput and output characteristics of which can be adjusted depending on the input ones is the topical problematic nowadays and, at least, for the closest future. We have investigated in the paper the possibilities of adjustment the considered filter's transmission characteristics through the ring design, distance between them, and discussed other features, which have impact. For example, it allows expanding of the filter bandwidth from 250 to 60 MHz for simultaneous change of a distance between the adjacent rings. We have suggested the approach how to do the filter time-dependent. A varactor diode inserted into the gap of the middle ring is controlled with an independent external source and can adjust the filter bandwidth from 80 up to 140 MHz for the varactor capacitance variation from 16 to 6 pF (bias voltage variation from 1 to 7 V) that covers the existing communication networks, such as mobile generations, Bluetooth, Wi-Fi, etc. and can be applied for modern smart technologies of the Internet-of-Things for a remote control. It becomes possible because different sensing elements, such as photodiodes, Hall effect sensors, photoresistors, etc., can be exploited as the aforementioned external source.

KEYWORDS ring resonator, bandpass filter, microstrip circuit, IoT devices.

I. INTRODUCTION

The advent of the era of the latest wireless communication systems from 4 to 5, and in the closest future, 6G, has led to the necessity of an increasing of the data rate [1-2]. The transfer into higher frequencies and faster communications lead to an increase in signal filtering devices [3], namely bandpass filters (BPFs) [4]. In a radio frequency (RF) transceiver module, the BPF plays a vital role. It filters out out-of-band interference and noise to meet the signal-to-noise ratio requirements of RF systems and communication protocols [5]. Currently, the development of compact and low-cost BPFs is urgent and is closely related to the usage of signal spectrum resources and the complexity of communication protocols [6]. In addition, as the number of frequency bands that mobile phones and other communication systems must support continues to increase, since each frequency band must have its own filter, the number of filters that must be used is also increasing [7].

Modern BPF design techniques have significantly evolved from the initial passive element-based circuits to modern microstrip filters, with multiple resonant elements in the form of microstrip elements (MEs) [8-10] placed on a printed circuit board (PCB) [11-12]. MEs are constructed in the form of various geometric shapes, which are inductive and capacitive circuits, thus forming a transmission line [13]. Such circuits provide the required filter bandwidth characteristics. ME allows to significantly diminish the size of the filter and simplify its manufacturing, and, thus, reduce its cost [13].

There are many different types of filters made in the form of a microstrip transmission line, which consist of an array of MEs [14]. There have been papers presented with different configurations of MEs for BPFs, such as end-coupled, parallel-coupled, interdigital, hairpin, and others [16-20]. The parallel-coupled is one of the most commonly used technique due to its simple design and relatively wide bandwidth [21]. In [22-23], broadband BPFs with the bandwidth of up to 60% were developed. Based on the new configurations shown in [24], the filters reach up to 80% bandwidth with low out-of-band rejection. In [25], a new method based on low-temperature ceramics was presented that result in very compact dimensions. Some BPFs require high selectivity at one of the edges of the bandwidth, and for this purpose, designs with an asymmetric frequency response are used in [26]. Such designs, unlike symmetrical ones, make possible improving the frequency response and reduce the number of MEs.

However, the characteristics of the considered filters are usually defined in advance and cannot be acquired in real-time in response to an input signal. Therefore, the ability to adjust the filter depending on the desired frequency range is an excellent solution. In the microwave frequency range, the use of a varactor diode [27-29] can provide the ability to control the bandwidth of a BPF. Such tuning is achieved by controlling the resonant frequencies, while changing the capacitance of the varactor by applying a bias voltage to it. In this article, we will consider the development of a compact time-controlled microstrip BPF with the ability to change the bandwidth characteristics in a narrow frequency range.

II. FILTER MODEL AND ITS FREQUENCY CHARACTERISTICS

The BPF model based on ring resonators [30] was chosen for the thoroughness study. The elaborated filter model, shown in Figure 1, is designed with the FR-4 dielectric substrate (relative permittivity ε = 4.3) with double-sided copper coating. The thickness of the dielectric substrate is 1 mm and the copper coating is 35 microns. The front layer (Figure 1, *a*) consists of three ring resonators with the following geometric dimensions: m = 13.16 mm, n = 13.16 mm, p_1 = 9.37 mm, p_2 = 9.87 mm, k = 1 mm, h = 0.257 mm and e = 0.5 mm. The resonant frequency and bandwidth of the filter depend on the value of the mentioned dimensions. The bandwidth and slope of the front and back faces of the BPF depend on the distance h between the ring resonators and their quantity. Each of the rings can be considered as an equivalent *LC*-circuit and is therefore characterized by a specific value of the resonant frequency. The other side of the dielectric substrate is completely coated with a copper layer, which is analogous to a transmission line (Figure. 1, *b*).

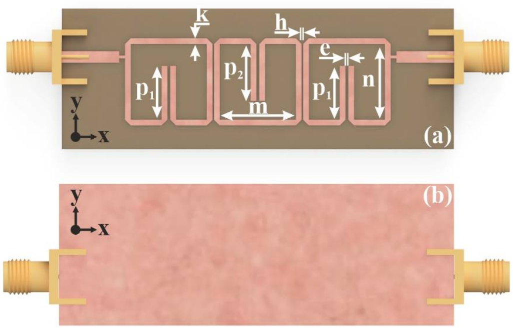

FIG. 1. Model of the designed BPF based on ring resonators: front (a) and back (b) sides.

For further investigation of the frequency response, the model of the filter with the previously-mentioned geometric dimensions was modelled in CST Microwave Studio. The filter was connected to the input and output waveguide power ports, which is the commonly used approach to simulate such type of structure. The spectra of the S_{21}-parameters were studied to show what proportion of energy transmitted from the input port is collected at the output one. Thus, according to the studies, the shown in blue graphs in Figure 2 can be seen and they practically coincide with the theoretically calculated data shown in Figure 2 with the red line. The center frequency of the filter is 1.1 GHz and the bandwidth is about 100 MHz at the cut-off frequency level of 0.707.

The theoretical calculations were carried out following the analytical analysis shown in [31]. The equivalent capacitance is presented as a capacitance between two parallel microstrip lines, while an inductance along the entire length of the microstrip line serves as an equivalent inductance. As mentioned above, the ring resonator is an *LC*-circuit. Thus, a value of the resonant frequency is determined according to the Thompson formula:

$$f = \frac{1}{2\pi\sqrt{LC}}. \quad (1)$$

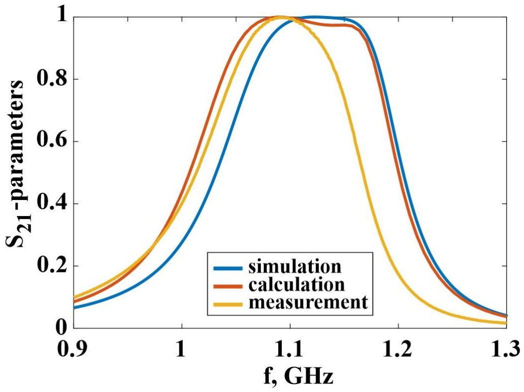

FIG. 2. Spectra of S_{21}-parameters obtained for theoretical calculations (red), simulation (blue), and experiment (yellow).

As a result of the analytical calculations and simulations, the needed parameters and frequency ranges were obtained to fabricate the experimental model and perform measurements then.

The experimental BPF were fabricated based on the investigated filter model and specified structural parameters (Figure 3). The BPF were fabricated by drawing the corresponding lines on the copper layer of a double-sided FR-4 PCB (ε = 4.3 and $tg(\delta)$ = 0.01), followed by chemical etching. The back was not treated, leaving the copper layer intact. SMA connectors with a characteristic impedance of 50 ohms are connected to each of the outputs for connection to the measuring instrument. The etched outputs' impedances were calculated to match them to the SMA connectors.

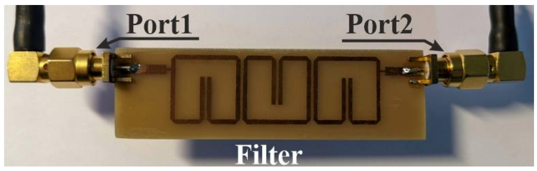

FIG. 3. Experimental model of the investigated filter.

For measurement of S_{21}-parameters, the input and output are connected to the two-channel vector network analyzer (nanoVNA). As a result of the measurements, the graph marked in yellow in Figure 2 shows that the outcomes of the experimental studies almost completely reproduce the previously obtained results of theoretical calculations and simulations. However, the bandwidth at frequencies reaches slightly lower values (80 MHz). It is due to the dielectric losses of the used substrate. From the obtained results, it can be concluded that the algorithm considered for the calculation of ring resonators and their simulation allow obtaining results that are in good agreement with the experimental results.

For a visual assessment of an operation of the filter, which is focused on the passage of high-frequency signals, the distributions of the EM field over the surface of the structure are displayed. Since a high-frequency current flows through the filter, it is advisable to consider the distribution of the electrical component of the EM field at the same plane with the ring resonators. The results were obtained in CST Microwave Studio and are shown in Figure 4. From the electric field distributions, it can be seen that transmission is not possible at 0.8, 0.9 and 1.3 GHz (Figure 4, *a-b, f*), since the maximum intensity (red colour of the distribution) is concentrated around two the first rings and does not reach the third one and the output port as a result. At the same time, all three ring resonators are coloured in the red for frequencies of 1, 1.1 and 1.2 GHz (Figure 4, *c-e*), which means that the field intensity is maximum there and an electric current can pass toward the output.

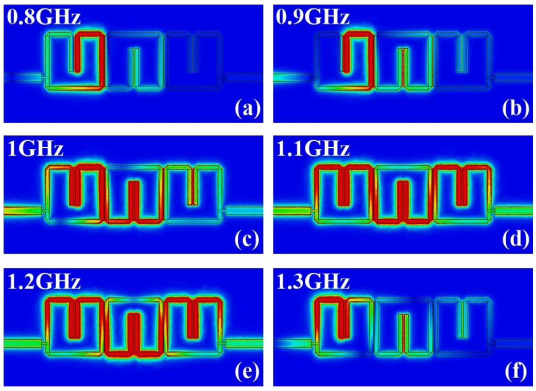

FIG. 4. Distributions of the electric component of the electromagnetic field on the filter surface.

III. THE FILTER BANDWIDTH CONTROL

Frequency or bandwidth control is important for multi-band and adaptive systems in order to cover the required frequency bands. As noted above, a frequency response of the BPF depends on the geometric and structural features of the ring resonators. To obtain a specific value of the central frequency, such parameters as *m, n,* p_1, p_2, and *e* must remain unchanged. Instead, the parameter *h* can control the operating frequency band (Figure 5, *a*). Thus, *h* = [0.37, 0.51, 0.66, 0.81, 0.96] mm was chosen during the investigation to demonstrate the effect. As a result, the S_{21}-parameters were obtained using CST Microwave Studio, which are shown in Figure 5, *b*. The plot shows that an increase in the value of the distance between the ring resonators leads to the decreasing in the operating frequency band, i.e., to a narrowing of the bandwidth, from almost 250 MHz up to ~60 MHz at the cut-off frequency level of 0.707.

However, this method does not allow changing or controlling the bandwidth in real time. One of the possibilities to achieve this task is a utilization of varactors. The approach is the well-known technique for adjustment of resonant frequencies by applying a bias voltage to it. Then the bias voltage controls both the resonant frequency and the bandwidth characteristic, which changes with variation of the varactor's capacitance.

For an experimental verification of the considered idea, the sample of the time-dependent filter was modified by mounting a varactor diode BB135 [32] in the gap of the central ring (Figure 6, *a*). The bias voltage was varied from 1 to 7V in 1V steps, which corresponded to a change in capacitance from 16 to 6 pF. Accordingly, the S_{21}-parameters were obtained, as shown in Figure 6, *b*. The plot shows that an increase in the bias voltage leads to a widening of the filter bandwidth. Thus, an increase in the bandwidth by ~140 MHz can be achieved.

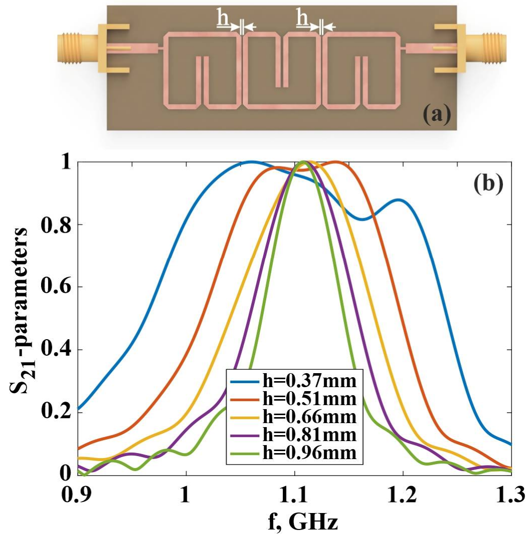

FIG. 5. The filter model showing the principle of frequency band control (a) and the obtained spectra of S_{21}-parameters at *h* = [0.37, 0.51, 0.66, 0.81, 0.96] mm (b).

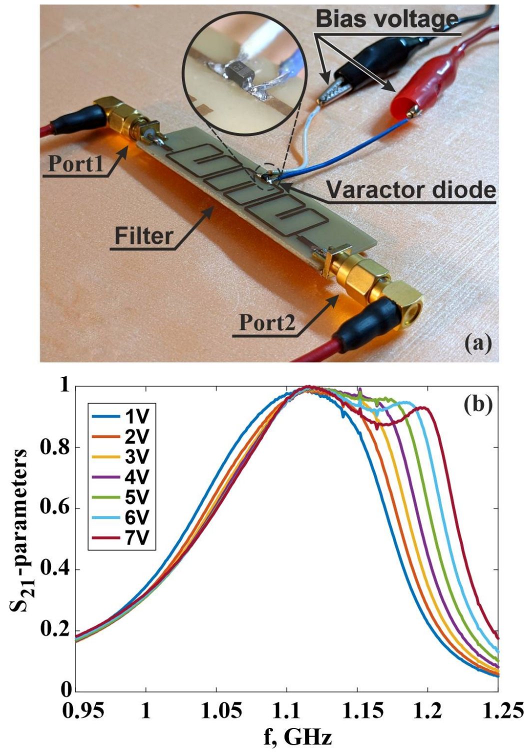

FIG. 6. Experimental model of the filter modified with a varactor diode (a) and the obtained spectra of S_{21}-parameters at changing the bias voltage (b).

IV. CONCLUSION

Adaptive filters, which belong to the modern type of filter devices, were considered in the paper. We have suggested time-variance exploiting for control of the output characteristics (bandwidth, central frequency, front and back slope) via the bias of a varactor diode that is inserted into the ring resonator gap. While the conventional time-invariant band-pass filters support the predefined parameters to provide the required transmission characteristics, the suggested one has a possibility to be adjusted within the frequency range from 80 to 140 MHz by changing the bias voltage from 1 to

7 V (changing the varactor capacitance from 16 to 6 pF). The considered approach of the filter design allows expanding the bandwidth up to 250 MHz on demand via changes of the geometrical parameters. The achieved bandwidth can cover a quite number of the existing bands of modern communication technologies such as mobile generations, Bluetooth, Wi-Fi, etc.

AUTHOR CONTRIBUTIONS

M.K., V.T., D.V. – conceptualization, methodology; M.K., V.T., M.A. – investigation; M.K., V.T., D.V. – writing (original draft preparation), M.K., V.T., D.V. – writing (review and editing).

COMPETING INTERESTS

The authors declare no competing interests.

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Регульований смуговий фільтр на основі кільцевих резонаторів для мікрохвильових застосунків

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АНОТАЦІЯ У статті представлено принцип побудови мікрохвильового адаптивного смугового фільтра на основі каскаду кільцевих резонаторів. Фільтр виконано у вигляді планарної мікросмужкової структури товщиною близько 1 мм для забезпечення компактності пристрою. Кільцеві резонатори входять до одного із класів метаматеріалів і можуть розглядатися як еквівалент коливального контуру, та зазвичай використовується в діапазоні низьких частот. Якщо фільтри з наперед заданими параметрами відомі, то адаптивні фільтри, пропускні та вихідні характеристики яких можна регулювати в залежності від вхідних, є актуальною проблемою сьогодення і, принаймні, найближчого майбутнього. У статті досліджено можливості регулювання передатних характеристик розглянутого фільтра за допомогою конструктивних особливостей кілець. Наприклад, одночасна зміна відстані між сусідніми кільцевими резонаторами від 0.37 до 0.96 мм дозволяє варіювати смугою пропускання від 250 до 60 МГц. Суть же запропонованого підходу, що висвітлюється у роботі, полягає у введені елементів, параметри яких можуть змінюватись в часі. В якості такого елементу використано варакторний діод – елемент, що здатний змінювати ємність від прикладеної до нього напруги (у нашому випадку від 16 до 6 пФ при зміні напруги від 1 до 7 В). Даний елемент вмонтовується у розріз середнього кільцевого резонатору та керується незалежним зовнішнім джерелом живлення. Це дозволяє здійснювати контроль смуги пропускання досліджуваного фільтра від 80 до 140 МГц. Такий пристрій може знайти застосування в сучасних системах комунікацій, таких як мобільні мережі стільникового зв’язку, Bluetooth, Wi-Fi тощо, а також може бути застосований для смарт-технологій Інтернету речей та дистанційного керування. Це пов’язано із тим, що в якості вищезазначеного джерела живлення можуть використовуватись різноманітні датчики, що керуватимуть пропускною здатністю фільтра в залежності від зовнішніх факторів впливу (наприклад, температури, інтенсивності освітлення, зміни тиску, зміни електромагнітного фону, тощо).

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