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A novel compact and high performance bandpass filter based on SIW and CMRC technique

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ABSTRACT

Based on the substrate integrated waveguide (SIW) and compact microstrip resonant cell (CMRC) technique, a compact and high performance planar bandpass filter (BPF) is proposed in this paper. The SIW cavity, which has the advantages of high quality and low insertion loss, provides a highpass characteristic. The CMRC structure etched on the top metal plane of the SIW cavity behaves as a lowpass filter, and it can also effectively reduce the dimension of the filter. In order to improve the out-of-band rejection and sharpen skirt selectivity, the open circuit lines at the input and output ports of the filter are introduced. Moreover, the bandwidth and center frequency of the proposed filter can be flexibly tuned by adjusting the cutoff frequencies of the SIW and CMRC separately. As a verification, a representative BPF having a center frequency of 4.54 GHz and a 3 dB bandwidth of 1.39 GHz is designed, fabricated, and experimentally evaluated. The simulated and measured results are in good agreement.

1. Introduction

Microwave bandpass filter (BPF) is the key component of wireless communication systems, it can control the spectrum of signals and tackle interference issue. With the rapid development of wireless communication technology, the demands of compact size, high performance, and low cost microwave bandpass filters (BPF) is explosively growing [1]. To satisfy the stringent requirements, more and more novel BPF structures are investigated and designed [2]. Meanwhile, a convenient and interesting planar integration scheme called substrate integrated waveguide (SIW) has already attracted a lot of research attentions. The SIW is a type of waveguide-like structure that can be fabricated on the planar dielectric substrate material by employing arrays of metallic via holes to emulate the ideal vertical walls [3]. It enjoys not only the advantages of rectangular waveguide features, but also the benefits of planar circuits, such as high quality factor (Q-factor), low insertion cost, high power-handling capability, light weight, mass-production, complete shielding, easy to fabricate by using standard printed circuit board (PCB) and good integration [4–6], thereby providing a promising platform to develop filters with compact size and good performance. A variety of excellent filters are designed based on SIW technology [7–9]. In [10,11], the SIW bandpass filter is proposed by employing arrays of metallic via holes to construct couple resonator cavities. In order to achieve great selectivity, the number of resonators has to be increased, and despite a high selectivity can be achieved, its bandwidth is hard to adjust. Besides, in [12], electric magnetic cross-coupling is introduced to improve the frequency selectivity, however a large size is made on single-layer substrate, especially at low frequency. In [13], a multilayer SIW is applied to obtain a bandpass filter with high selectivity, but the structure certainly increases the circuit complexity and design difficulty. At the same time all these methods are based on the coupled-resonator topologies. Those resonators resonate at the in-band frequencies and have a limited quality factor which is much lower than the waveguide resonators. As a result, the conventional SIW bandpass filters still suffer from the increased loss resulted by the coupled-resonators though its insertion loss is much smaller than the microstrip filters. Moreover, because the couplings among resonators vary with the operating frequency, the coupled-resonator filter can only be appropriate for narrowband applications [14]. The most important thing is that all these SIW filters mentioned above is relative bulky for highly integrated filter designs. In [15], some compact SIW filters are designed by combining the defected ground structure (DGS). Some patterns such as dumbbell-shaped or horseshoe-shaped have to be etched on the bottom surface of the SIW cavity. Although they are low cost, compact size, easy fabricated and excellent performance, the etched ground plane must be far from any metal plant in order to keep the etched patterns in function. This results in a packaging problem with a metal shielding box [16].

In order to reduce the size of SIW filter and improve its design flexibility, a novel structure have to be invented. In 2000, the compact

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microstrip resonant cell (CMRC) was proposed by Professor Q. Xue of the City University of Hong Kong. It is a slow-wave structure with a compact size, high selectivity and low insertion loss. At the resonant frequency, the cell exhibits a low-pass characteristic. So it is often used to design lowpass filters and bandpass filters.

In this letter, the CMRC resonators are etched on the top metal plane of the SIW cavity to form a novel well-behaved and compact bandpass filter, which takes full advantage of the characteristics of SIW and CMRC. By properly adjusting the cutoff frequencies of the SIW cavity and CMRC resonator, the desired bandwidth and center frequency can be easily achieved. Moreover, the BPF is not based on the coupled-resonator topologies, so the proposed BPF can be designed with high quality factor and low insertion loss. As demonstrations, a bandpass filter with a 1.39 GHz bandwidth centered at 4.54 GHz is proposed by using three-order CMRC-SIW units. The design methodology is presented step by step. The structure of the BPF is modeled by full-wave simulator HFSS and fabricated on Rogers4350B substrate ($\varepsilon_r = 3.66$) with a thickness of 0.508 mm. Finally, it is rigorously measured. All the simulated and measured results are in good agreement with the predicted data, thus verifying the proposed concept and the effectiveness of the design method.

2. Filter design and simulation

2.1. SIW highpass filter

As shown in Fig. 1, the SIW cavity is a basic element of the proposed BPF, which is constructed using two series of metallic vias over a substrate sandwiched between two copper layers. It can thus be considered as a planar circuit transformation of non-planar rectangular waveguide (RGW) [16]. So the cutoff frequency of the SIW can be obtained by the following equation through its modeling by an equivalent RWG [15].

$$f_c = \frac{c_0}{2\sqrt{\varepsilon_r}}\left(W_{SIW} - \frac{d^2}{0.95P}\right)^{-1} \quad (1)$$

where c_0 is the light velocity in vacuum, ε_r is the relative permittivity of the substrate, W_{SIW} is the width of the SIW, the distance between adjacent metallized vias is denoted by P, and d represents the diameter of metallized vias.

However, the SIW cannot be considered as an ideal homogenous rectangular waveguide. The gap between the aligned metallic vias may trigger frequency-dependent leakage losses, which are mainly determined by the parameters P and d [16]. Therefore, in order to minimize the loss of typical SIW structures, the following design principles must be observed [17]:

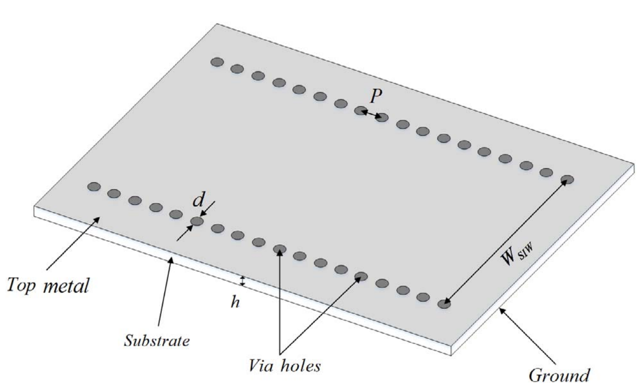

Fig. 1. Configuration of the substrate integrated waveguide.

$$\begin{cases} d < 0.2\lambda_{gsiw} \\ d/W < 0.2 \\ d/p \geqslant 0.5 \end{cases} \quad (2)$$

where λ_{gsiw} is the guided wavelength of SIW, and it can be obtained by using the following relation:

$$\lambda_{gsiw} = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{2W_{SIW}}\right)}} \quad (3)$$

where λ_0 is the wavelength in vacuum and W_{SIW} is the width of SIW. Based on these empirical relations, the SIW can be designed as a highpass filter [18]. However SIW filters mentioned above are still bulky for highly integrated filter designs especially at low frequencies. So some changes have to be done on the SIW structure to reduce its size in some filter applications.

2.2. CMRC lowpass filter

In the past few years, researchers have found that the size of microstrip circuits can be effectively reduced by introducing a slow-wave structure. The compact microstrip resonant cell (CMRC) shown in Fig. 2 is an effective microstrip transmission line which exhibits slow-wave and stopband characteristics.

A CMRC with a new pattern is proposed in this paper, it consists of some thin lines. As we can see, the width of all the thin lines are the same, but they have different lengths so that they can resonate at different frequencies, which provide alternative choices for various applications.

According to the transmission line theory, the propagation constant of a lossless line is:

$$\beta = \omega_0\sqrt{LC} \quad (4)$$

where ω_0 is the angular frequency, L and C are the distributed series inductance and shunt capacitance per unit length, respectively. Therefore, the wave velocity of electromagnetic waves in the lossless microstrip line can be obtained by:

$$v = \frac{\omega_0}{\beta} = \frac{1}{\sqrt{LC}} \quad (5)$$

Obviously, these thin lines in the CMRC will increase the series inductance while the gap between the lines increase the shunt capacitance, which thus increase the propagation constant and decrease the wave velocity, resulting in the slow-wave effect. In addition, the increase of the series inductance is not linearly proportional to that of the shunt capacitance, the inductance increases more than the capacitance with the frequency. As a result, the characteristic impedance of the CMRC section, $Z = \sqrt{L/C}$, deviates from the impedance of microstrip input or output ports and hence causes the reflection which is larger in high frequencies, that is why the CMRC can perform as a lowpass filter [19].

2.3. Bandpass filter and its initial size

Considering the insertion loss, out-of-band rejection, size and other parameters, a third-order bandpass filter is proposed by combining the characteristics of SIW cavity and CMRC resonators. Fig. 3 shows the planar and three-dimensional (3D) structure of the proposed BPF, which consists of four parts, namely SIW cavity, CMRC resonators, tapered microstrip gradient lines and open circuit lines. The filter is excited by two 50 Ω microstrip lines. The ground is constructed completely by a metal and the used substrate is Rogers 4350B with the thickness $h = 0.508$ mm, permittivity $\varepsilon_r = 3.66$, loss tangent $\tan\delta = 0.0037$.

It is well known that a SIW structure can be considered as a conventional dielectric-filled rectangular waveguide with an effective