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A Compact Slow-Wave Filter with Double-sided Selectivity and Wide Out-of-Band Rejection

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***Abstract*—In this paper, a miniaturized filter with double-sided selectivity and wide out-of-band rejection is presented. The slow-wave and negative cross-coupling structures are effectively adopted to realize an ultra-compact K-band filter with two symmetric transmission zeros. Starting from a bandpass filter configured for a center frequency of 18.5 GHz and the main-line couplings that only exhibits a good out-of-band rejection of 30 dB up to 30 GHz, the two proposed negative cross-couplings enable the steep roll-off out-of-band rejections as well as low in-band insertion losses of 1.7 dB and 2.4 dB. The designed structures are utilizing both the additive manufacturing and PCB-based technology which in turn, provide a simple, low-profile, and cost-effective fabrication process for highly integrated RF systems, particularly in satellite applications.**

***Index Terms*—K-band filter, negative coupling, slow-wave, transmission zero.**

I. INTRODUCTION

Future generations of telecommunication systems will exhibit a deeper integration – or even convergence – of fixed and mobile services. Scenarios have been identified were satellite systems and in particular LEO satellite mega-constellations, can support 5G architectures to improve the connectivity of IoT devices in remote areas. Besides managing the intersystem handover and security issues, other challenges have been identified. One of which is associated with the economic utilization of the limited spectrum and the use of higher frequencies. For that purpose filters are essential building blocks which demand low-profile, lower losses, strict passband performance, and good out-of-band rejection [1].

Slow-wave microwave components are a branch of metamaterials that provide good performance in terms of out-of-band rejection and size reduction, making them a good candidate to address the strict requirement of satellites. Many investigations have been made to exploit the benefits of slow-wave structures in implementing microwave and mm-wave components [2], [3]. One of the worthy mentions is the implementation of slow-wave substrate integrated waveguide (SW-SIW) [2], where the slow-wave effect inside the SIW was created by an array of periodic blind vias inside the propagation medium. The SW-SIW reported in [2] achieved a longitudinal size reduction of better than 40% compared to a conventional SIW. There is also a recent study of a slow-wave filter implementation in the SIW platform [4], [5], where the implementation of inductive post and iris coupling has been investigated. Both of the filters exhibit a significant size reduction. However, it is shown in the results that the insertion loss is high due to the dielectric losses. In some other literature, a type of slow-wave structure is introduced, where it is referred to as meta-substrate structure. These meta-substrate structures also show significant improvement in miniaturization of microwave components such as patch antennas [6] or SIW cavities [7]. All of these components are designed for the lower spectrum of microwave frequencies.

Despite the compactness of these planar solutions, one significant setback in the implementation of slow-wave structures in a planar solution were the increased losses, especially at higher frequencies. One method of reducing losses at higher frequencies was to remove the dielectric substrate to eliminate the dielectric losses [8], [9]. Reference [9] proposes a semi-planar structure which has the advantage of compactness and high quality factor performance. Additionally, having a PCB layer as the top layer provides opportunities to create paths for waves through the PCB layer to create negative coupling. Moreover, the filter component can be used as surface mountable component which can be interesting in some applications.

The implementation of a semi-planar air-filled SW filter has challenges of its own and requires further investigation. This paper investigates two different methods for implementing a negative coupling in the proposed SW filter configuration. All three proposed structures show low losses due to the elimination of dielectric loss from the structure. The two proposed negative couplings created symmetrical transmission zeroes around the passband, thus improving the filter's frequency selectivity. Furthermore, the slow-wave filters show improved out-of-band rejection because of the SW's frequency selective characteristic, which is a desirable factor in practical filter design. In the end, a comparison between the three filter configuration is made and a conclusion based on the achieved results is drawn.

II. SLOW-WAVE FILTER DESIGN

A. *Slow-wave Unit-cell and resonator*

The working principle of slow-wave structures is based on reducing the group velocity of the transmission line by creating an array of periodic structures in the wave propagation path. The unit cell design is decided based on the upper out-of-band rejection specification and the required miniaturization. The stop-band of the unit cell can be utilized to achieve an even better out-of-band rejection. The dispersion diagram of the proposed unit cell is shown in Fig. 1. The stopband of the proposed unit cell is in the frequency band of 62 to 95 GHz, while the designated slow-wave passband is from 17 to 20 GHz. Therefore, an excellent out-of-band rejection can be achieved with a careful design of unit-cell resonators and input and output coupling.

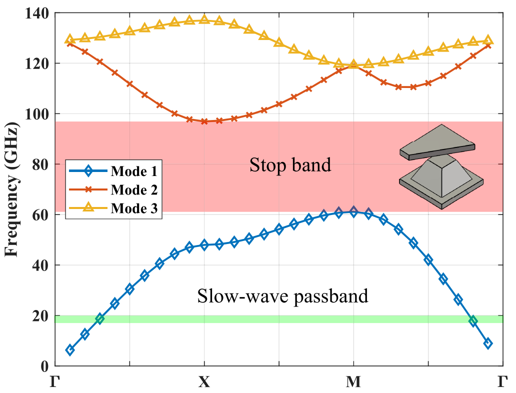


Fig. 1: Dispersion diagram of the slow-wave structure over the irreducible Brillouin zone ($\Gamma-\mathrm{X}-\mathrm{M}-\Gamma$).

Additionally, to demonstrate the slow-wave effect of the proposed structure, the phase velocity was plotted versus the frequency for different values of pin's height. It is shown in Fig. 2 that the bigger the height of the pins are with respect to the cavity, the slower is the phase velocity of the proposed structure. The resonator created with the proposed unit-cell shows a size reduction of equal to 41% compared to a conventional resonator of the same shape without the pins.

B. Inline filter and negative coupling implementation

A four-pole inline filter was designed using the proposed slow-wave resonators, with an insertion loss of 1.7 dB at the center frequency of 18.5 GHz and a bandwidth of 400 MHz. The proposed filter has a lower roll-off factor of 6.1 dB/100 MHz, an upper roll-off factor of 7.9 dB/100 MHz and an out-of-band rejection of better than 30 dB up to 30 GHz. The substrate used for the proposed structure is from the Rogers company (RO4350B), with a thickness of 0.508 mm, dielectric constant of $\varepsilon_r = 3.66$ and dissipation factor of $\tan\delta = 0.0037$. The frequency response of the filter, as shown in Fig. 3c, has an acceptable performance in terms of loss and out-of-band rejection.

As a complementary, the filter selectivity was improved by implementing transmission zeros around the passband. Two possible solutions for achieving a negative coupling were simulated: either through the substrate integrated waveguide on top or from a GCPW coupling through the top conductor of the resonator. The non-zero elements of the coupling matrix of the proposed filter have the following values: $M_{S1} = M_{4L} = 0.91$, $M_{12} = M_{34} = 0.79$, $M_{23} = 0.676$, $M_{14} = -0.071$. The aforementioned couplings and external quality factor and corresponding physical dimensions of the filter can then be calculated through the following expressions:

$$K = \frac{f_{\mathrm{High}}^2 - f_{\mathrm{low}}^2}{f_{\mathrm{High}}^2 + f_{\mathrm{low}}^2},\ Q_{\mathrm{ext}} = \frac{2f_0}{\mathrm{BW}_{-3\ \mathrm{dB}}}, \tag{1}$$

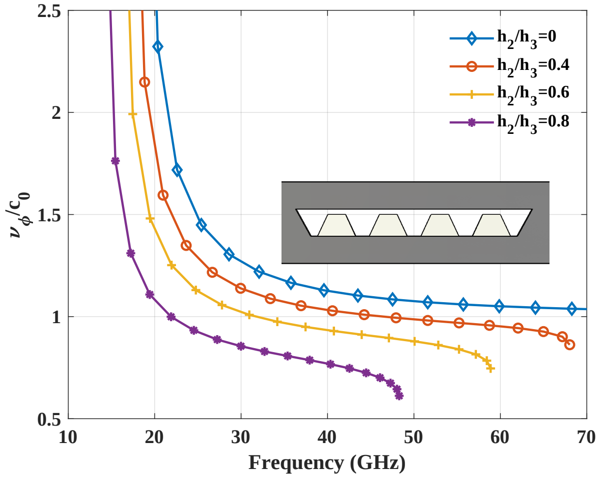
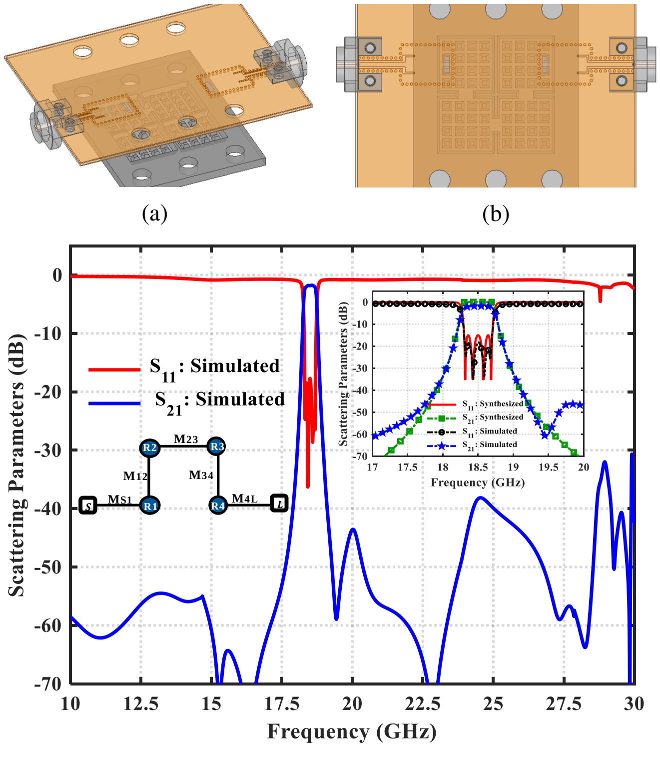


Fig. 2: Normalized phase velocity (ν_ϕ/c_0) versus frequency for different relative heights of pins (h_2) to the height of the cavity (h_3).

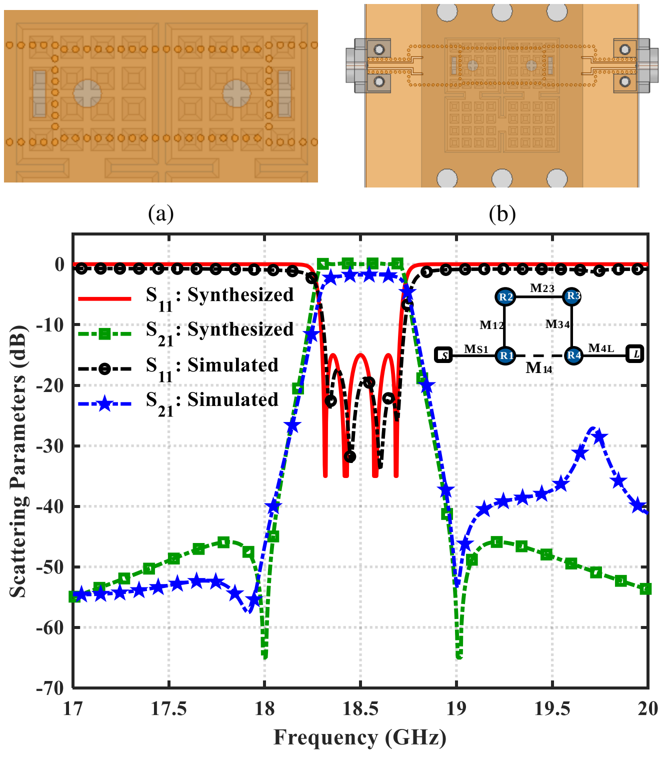


(a) (b)

(c)

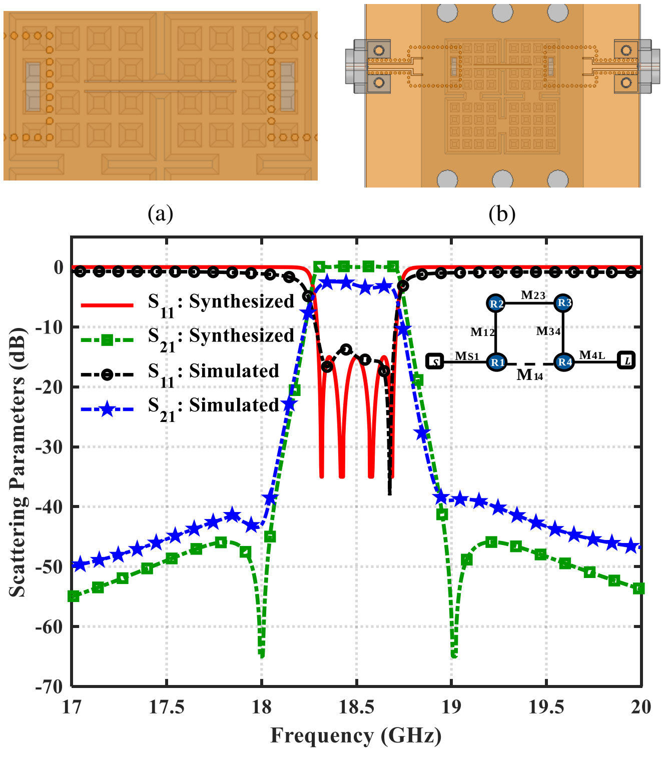
Fig. 3: (a) 4-pole filter inline filter, (b) top view of filter, and (c) out-of-band rejection performance of filter.

The two possible solutions along with the frequency responses are shown in Fig. 4a and Fig. 5a, respectively. These filters were simulated through the frequency domain engine of CST 2020, and the results were confirmed using the HFSS software. The Fig. 4a solution provides the filter response with a roll-off factor of 13.8 dB/100 MHz and upper roll-off factor of 18.9 dB/100 MHz, which provides better selectivity compared to the inline configuration. The second solution also provides a good roll-off factor of 13.9 dB/100 MHz and upper roll-off factor of 15.7 dB/100 MHz. The negative coupling



(c)

Fig. 4: First proposed filter (a) negative coupling structure-1, (b) top view, (c) filter response inset with topology.



(c)

Fig. 5: Second proposed filter (a) negative coupling structure-2, (b) top view, (c) filter response inset with topology.

provided in both solutions are realized by transferring the peak of electrical fields of the first resonators to that of the fourth resonator. The first solution shows a filter response with lower insertion loss than the second solution because the slots on top of the resonator can cause an increased leakage loss.

III. CONCLUSION

In this communication, we described the implementation of two negative coupling solutions which can effectively improve the frequency selectivity, in-band insertion loss, and overall size of an inline slow-wave filter with the same filtering specifications but more number of resonators. The two proposed filters feature a lower roll-off factor of 13.8 dB/100 MHz and 13.9 dB/100 MHz and an upper roll-off factor of 18.9 dB/100 MHz and 15.7 dB/100 MHz, respectively. The proposed filter has the advantages of low-loss, high selectivity, good out-of-band rejection, and low-profile.

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