Multi-layered PCB distributed filter

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Introduction: There exists a strong interest in the telecommunications industry for cost-effective and low-volume resonators and filters, driven, primarily, by the need for increased integration. Usually, such filters come in the form of ceramic-filled coaxial TEM filters or ceramic waveguides, depending on the required performance level [1, 2]. However, the compact size of such devices comes at the cost of reduced performance, due to the losses of the ceramic materials.

Traditionally, RF filters have tended to occupy a large portion of the real estate of the entire transceiver, which, in a typical base station scenario, required the transceiver board to be mounted on top of the aluminium block containing the required duplexers. For medium power transceivers, the filtering requirements can be relaxed, enabling the use of smaller-size ceramic filters. However, for the frequencies of the majority of current telecommunications systems, operating around and below 2 GHz, the size of such filters still tends to cause problems. The main issue lies with the fact that such filters need to be surface mounted, which increases the overall height of the entire TRX board. On the other hand, there exists a relatively large and unused volume under the transceiver board circuitry, currently unused.

In this paper, we propose a new family of distributed resonators, which can be integrated into the standard multi-layered PCB. The distributed and PCB resonator concept has been successfully demonstrated in [3, 4], where it was shown that low profiles of the order of $10^{-5}$–$10^{-6}$ are possible. The principle of operation of distributed resonators relies on the mutual coupling of the elements placed inside the cavity. The number of elements inside the cavity together with the degree of inter-element coupling ultimately determine the reduction of the profile of the obtained resonator. For the purpose of increased inter-element coupling, the individual elements are positioned in an inter-digitated form. The multi-layered PCB resonators introduced in this paper offer much lower profiles than those in [3, 4], down to $5\times$, which is the lowest profile to be reported in the literature. The filter was made to operate at a centre frequency of 1.8 GHz with an absolute bandwidth of 65 MHz. The measured and computed results are in good agreement.

FIG. 1 11 × 11 multi-layered PCB integrated distributed resonator – (a) perspective view, (b) cross-section perspective view, (c) magnified cross-section view

In this paper, multi-layered print circuit board distributed resonators and filters are introduced. Here, the individual elements of the distributed resonator are made as part of a multi-layered print circuit board, commonly used in the circuitry of transceiver boards. In this way, the unused real estate available on the board is used effectively. As a demonstrator of the proposed technology, a 2-pole filter fabricated using a 5-layer substrate and consisting of a matrix of 11 × 11 elements per resonator is fabricated and its performance is measured. Due to a large number of individual elements, which perform dimensional averaging of manufacturing inaccuracies, the filter obtained in this way not only requires no post-production tuning, but it also has an extremely low profile of $5\times$, which is the lowest profile to be reported in the literature. The filter was made to operate at a centre frequency of 1.8 GHz with an absolute bandwidth of 65 MHz. The measured and computed results are in good agreement.

The multi-layered PCB resonator: The proposed multi-layered PCB resonator is shown in Figure 1. The resonator consists of a matrix of 11 × 11 conductive elements, integrated into a five-layer PCB substrate. Each element has an annular ring at its open end, due to the fabrication process, as a consequence of the need for silver plating. The number of individual elements and, hence, the size of the resonator matrix is chosen in the way to filter out the inaccuracies arising due to manufacturing. This is performed using a yield analysis with the goal that the change in the frequency of operation as a function of manufacturing tolerances of the height of the elements, their diameter and spatial position is less than 0.01%.

Simulated and experimental results: In order to demonstrate the feasibility and potential of the proposed multi-layered PCB distributed resonator, a two-pole Chebyshev filter is designed, simulated and fabricated. The filter is made to operate at a centre frequency of 1.8 GHz with an absolute bandwidth of 65 MHz and a minimum return loss of 16 dB. The coupling matrix of such a filter can be written as

$$K = \begin{pmatrix} 0 & 0.04913 \\ 0.04913 & 0 \end{pmatrix}$$ (1)

This yields the value of the corresponding external coupling coefficient of $Q_e = 23.67$. The resonator used for this purpose is shown in Figure 1. The multilayered substrates used in the simulations and fabrication are from Tachyon [8]. With reference to Figure 1, the heights of the corresponding substrates are: the heights of layers 1 and 5 are the same, $h_1 = h_5 = 0.254$ mm, the heights of layers 2 and 4 are also the same with $h_2 = h_4 = 0.129$ mm, while the middle layer has the height of $h_3 = 0.508$ mm. As such the total, combined height of the filter is $h = 1.274$ mm. This makes the entire individual resonator volume equal to $40 \times 40 \times 1.274$ mm$^3$. The dielectric characteristics of the substrates are $\varepsilon_{i1} = \varepsilon_{i5} = 3.04$ with $\tan(\delta_1) = \tan(\delta_5) = 0.0016$, $\varepsilon_{i4} = \varepsilon_{i4} = 3.11$.
The height of the annular ring is 3.25 mm and \( \tan(\delta_3) = 0.0018 \) and \( \tan(\delta_4) = 0.0022 \). The radius of the individual element is 1 mm, while the radius of the corresponding annular ring placed on top of each element is 1.2 mm. The height of the annular ring is 35 \( \mu \text{m} \). The heights of the individual conductive elements are the same and equal to \( Z_{\text{via}} = 0.891 \text{ mm} \) and are, effectively the sum of heights of \( h_1, h_2 \) and \( h_3 \). The edge-to-edge separation between the consecutive elements is uniform and equal to \( d = 0.75 \text{ mm} \). The unloaded \( Q \) factor of the resonator is approximately 300 and this value was obtained using a commercial full-wave simulator, CST [9]. Here, it was assumed that the resonant elements are adequately silver plated, with a conductivity that is 15\% lower than that of pure silver, so as to take into account possible imperfections of the silver-plating process and increased levels of surface roughness. The designed two-pole filter is shown in Figure 2. The inter-resonator coupling in the present design is performed in a conventional way, using an iris, as depicted in the figure. The dependency of the coupling coefficient on the iris width is shown in Figure 3. The width of the iris used for the purpose of this figure was 2 mm. It can be seen from this figure that the proposed resonator is able to couple strongly, depending on the iris opening. The coupling between the resonators is magnetic [10]. Electrical (negative) coupling can be accommodated using the approach presented in [6], which uses a slot in the coupling iris.

The iris opening in the designed filter equals 19.04 mm. The filter takes place at a frequency of approximately 2.9 GHz, which results in a spurious-free window of about 1.1 GHz. In relative terms, the first discrepancy between the measured and simulated inserting losses is likely due not only to the increased surface roughness of the fabricated device but also due to a possibly reduced conductivity compared to the one used in the simulations. The wideband performance of the fabricated filter is presented in Figure 9. This figure shows that the first spurious response takes place at a frequency of approximately 2.9 GHz, which results in a spurious-free window of about 1.1 GHz. In relative terms, the first spurious response occurs at a frequency that is approximately 1.6 times
greater than the centre frequency of the filter’s fundamental response. It is believed that the width of the spurious free window can be increased by carefully tailoring the coupling among the elements and, possibly, by placing short circuits at the positions of the maxima of the electric fields of the spurious responses. Of course, care must be exercised so that the electric fields at the fundamental frequency are minimally disturbed.

**Conclusion:** In this paper, a filter based on multi-layered PCB distributed resonators is presented. The presented filter is fabricated using a 5-layer substrate and consists of an $11 \times 11$ matrix of elements per individual resonator. The fact that each resonator consists of 121 elements makes it immune to its manufacturing inaccuracies, that is, the resonator structure performs inherent dimensional averaging. This is extremely beneficial for the design of filters that require no post-production tuning. As a demonstrator, a two-pole filter is built, and its performance is measured. Its agreement with the predicted response is excellent. The increased number of elements is additionally beneficial for the achievement of extremely low-profile filters. The two-pole filter presented in this paper has an electrical height of less than 5mm.

**Conflict of interest:** The authors declare no conflict of interest.

**Data availability:** Data available on request from the authors.

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