# Design of Wide-Band Semi-Lumped Bandpass Filters Using Open Split Ring Resonators

Jesús Martel, Jordi Bonache, *Student Member, IEEE*, Ricardo Marqués, *Member, IEEE*, Ferran Martín, *Member, IEEE*, and Francisco Medina, *Senior Member, IEEE*

***Abstract*—Open split ring resonators (OSRRs) are used in this letter to design wide-band semi-lumped bandpass filters. OSRRs work as lumped $LC$ series elements due to their small electrical size and can be then used as building blocks of reduced size band pass filters. The values of the capacitance, $C$, and inductance, $L$, of the OSRR are controlled by adjusting the geometrical parameters of the coupled open rings. In our design, the OSRRs are connected through quarter-wave lines which act as inverters. The impedance of these inverters have been conveniently calculated to achieve the filter specifications. Finally bending and/or meandering techniques have been applied so as to obtain highly compact designs. Experimental verification is provided and good agreement has been found between electromagnetic simulations and measurements.**

***Index Terms*—Open split ring resonators (OSRRs), wide-band bandpass filters.**

## I. Introduction

The open split ring resonators (OSRRs) see Fig. 1(a) were proposed for the first time in a previous work of the authors [1] as a new series $LC$ particle very promising for the design of relatively small size bandpass filters. Two features of this particle must be emphasized regarding its application in filter design: very small electric size (typically one tenth of the free space wavelength) and wide band response. These properties can be explained because of the large distributed capacitance existing in the coupling region between the two rings. Thanks to this large capacitance, the resonance frequency of this particle is smaller than of other loop resonators of similar physical size working under $\lambda/2$ operation. Thus, strong coupling and small size lead to consider OSRR a very interesting building block to design wide-band bandpass filters [2]. In [1], the authors focused their attention on the analysis of the circuit model of the OSRR [see Fig. 1(b) itself] making comparisons with the split ring resonator (SRR) analyzed in [3]. A quasiperiodic structure implemented by cascading three identical stages like that in Fig. 1 was presented to demonstrate the filtering advantages of the OSRRs. However, it is well known that truncated periodic structures terminated in the usual 50-Ω impedance will present reflections (except if the Bloch impedance is matched to the line) and, therefore, there is no true control on the passband ripple [4]. The goal of the present work is the synthesis of a bandpass filter based on OSRRs using the standard Chebyshev filter design method, in such a way that filter specifications (central frequency, bandwidth and bandpass ripple) can be truly fulfilled. In order to achieve this goal, we have used the generalized network scheme shown in Fig. 2, which consists of a number of semilumped series $LC$ elements connected through impedance inverters (distributed elements) [5]. The network model in Fig. 2 exhibits a great flexibility to design bandpass filters because filter specifications can be reached with various combinations of the resonator parameters, $L_i$ and $C_i$, and normalized characteristic impedances of the inverters, $K_{ij}$. There are two obvious possibilities: in the first case, all the inverters are imposed to have $K_{ij} = 1$ (i.e, the inverters are $\lambda/4$ transmission lines with the usual characteristic impedance $Z_0 = 50$ Ω) and therefore the design algorithm provides different values of $L_i$ and $C_i$ for each filter stage; the second simple option, used in this work, is employing the same resonator for all filter stages (therefore the values of $L_i$ and $C_i$ are equal and we will refer to them as $L$ and $C$) and subsequently obtaining different values of $K_{ij}$ for

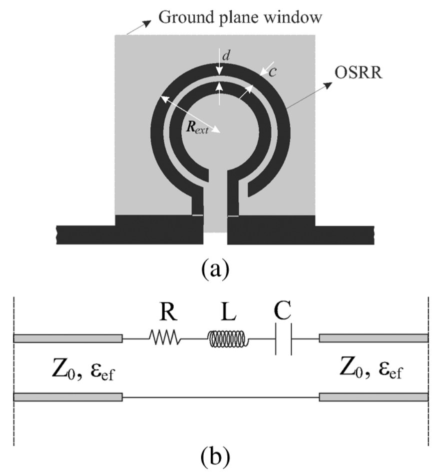


Fig. 1. (a) Open split rings resonator (OSRR) excited by a microstrip transmission line. (b) Equivalent circuit.

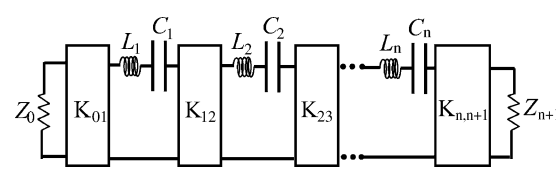


Fig. 2. Generalized bandpass filter network with impedance inverters and series $LC$ resonators.

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J. Martel, R. Marqués, and F. Medina are with Grupo de Microondas, Universidad de Sevilla, Sevilla . 41012, Spain (e-mail: martel@us.es; marques@us.es; medina@us.es).

J. Bonache and F. Martín are with the Departament d'Enginyeria Electronica. Universitat Autonoma de Barcelona, Barcelona 08193, Spain (e-mail: jordi.bonache@uab.es; ferran.martin@uab.es).

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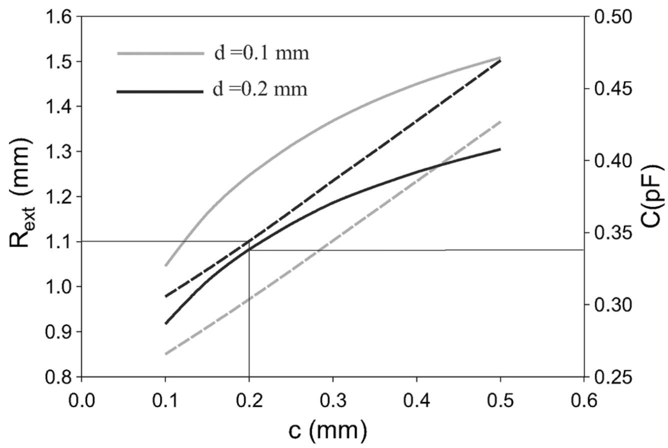


Fig. 3. External radius (solid line) and capacitance values (dashed lines) versus strip width of OSRRs whose resonance frequency is $f_0$, using the separation between rings, $d$, as parameter. The results are obtained for the cases $d = 0.1$ mm and $d = 0.2$ mm.

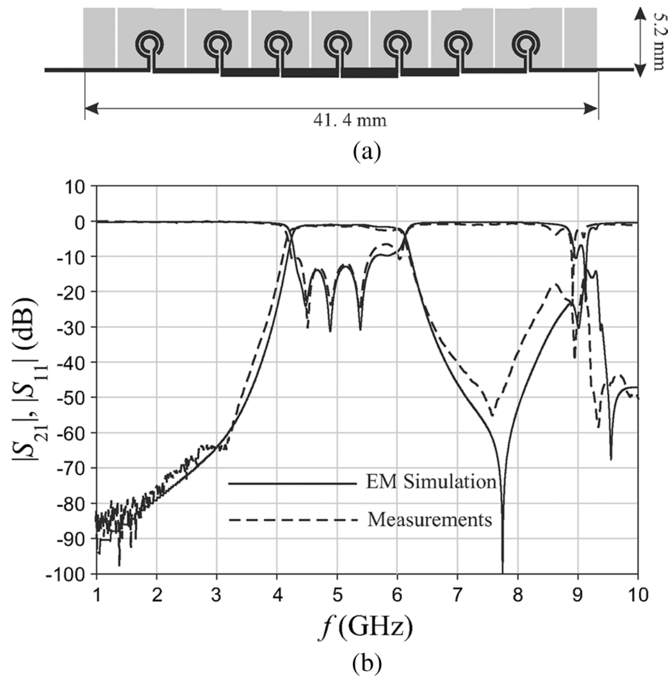


Fig. 4. (a) Final layout of the designed filter. (b) Measurements and EM simulations of the filter response.

the inverters. We have chosen this second possibility because the computational effort required to find the dimensions of a transmission line with a given characteristic impedance is less than of required to find the geometry of an OSRR with given values of $L$ and $C$. The steps followed in a selected filter design are described in detail in Section II. Bending and meandering techniques have been applied to the designed prototype to obtain more compact designs. Experimental confirmation of the theory is provided in Section III.

## II. Filter Design

In this section, we present the design and fabrication of a bandpass filter with central frequency $f_0 = 5$ GHz, bandwidth $\Delta = 40\%$ and ripple $rp = 0.01$ dB using a commercial substrate of relative dielectric permittivity $\epsilon_r = 10.2$ and thickness $h = 0.254$ mm. A filter order of $N = 7$ has been chosen in order to achieve good rejection in the out-band region. For the used substrate we have generated the design graph shown in Fig. 3. From this graph we can extract the geometry (external radius, $R_{\mathrm{ext}}$, and strip width, $c$; see Fig. 1(a) of all the possible OSRRs whose resonance frequency match $f_0$ for two different values of the separation between the rings, $d$. We also show in Fig. 3 the values of the corresponding capacitance $C$ (the values of $L$ can be easily obtained taking into account that $L = [(2\pi f_0)^2 C]^{-1}$). Data plotted in Fig. 3 have been calculated by using the model for the simple split ring resonators (SRRs) presented in [3] taking in mind that the inductance of both particles is the same while the capacitance of the OSRR is, approximately, four times that of a SRR with identical dimensions. For simplicity we have not considered losses in the analysis, in such a way that the resistance, $R$, of the circuit model in Fig. 1(b) is assumed to be negligible. In Fig. 3, we have marked the dimensions of the OSRR that we have selected for the filter implementation. The geometrical parameters of the OSRR are $d =$ 0.2 mm, $c = 0.2$ mm, $R_{\mathrm{ext}} = 1.101$ mm, and the circuit parameters are $C = 0.338$ pf and $L = 2.99$ nH. For these values, we have obtained from the standard filter design algorithm [5] the characteristic impedances (after the 50-$\Omega$ impedance scaling) of the involved inverters: $K_{01} = K_{78} = 48.6\ \Omega$, $K_{12} = K_{67} =$ 35.7 $\Omega$, $K_{23} = K_{56} = 24.1\ \Omega$ and $K_{34} = K_{45} = 22.2\ \Omega$. The next step is to find the geometry (strip width and transmission line length) of these inverters taking into account the presence of the windows see Fig. 1(a) practiced in the ground plane (these windows are used in order to not perturb the electromagnetic (EM) behavior of the OSRRs [1], [3]). This task has been carried out by using the quasi-TEM code presented in [6] for the analysis of hybrid CPW-microstrip structures. Although in the analysis we have considered the OSRR as a lumped $LC$ element, actually the particle introduces some phase delay; this fact has been taking into account and the lengths of the inverters provided for the code of [6] have been conveniently shortened in such a way that the phase delay of each filter stage is 90° at $f_0$, as it corresponds to the performance of the $\lambda/4$ inverters. This adjustment has been carried out by using the EM simulator (Ensemble).

## III. Experimental Results

The final layout and overall filter dimensions are shown in Fig. 4(a). As it can be seen in Fig. 4(b), a good agrement has been found between the measurements and the EM simulation of the filter response. The central frequency of the filter (5.15 GHz) is only slightly larger than of the designed filter, demonstrating that the approximate model used to characterize the OSRR provides very good results. The bandwidth of the implemented filter is $\Delta = 36\%$ and the rejection curve at both sides of the pass-band looks to be very symmetrical. As expected for this kind of filter, a spurious band appears at higher frequencies. In spite of the losses, which can be important in relatively high order filters as the one designed in this work, the insertion losses in the pass band are below 1 dB. In order to compact the filter, we have applied, respectively, bending and meandering techniques to the prototype of Fig. 4(b). In both

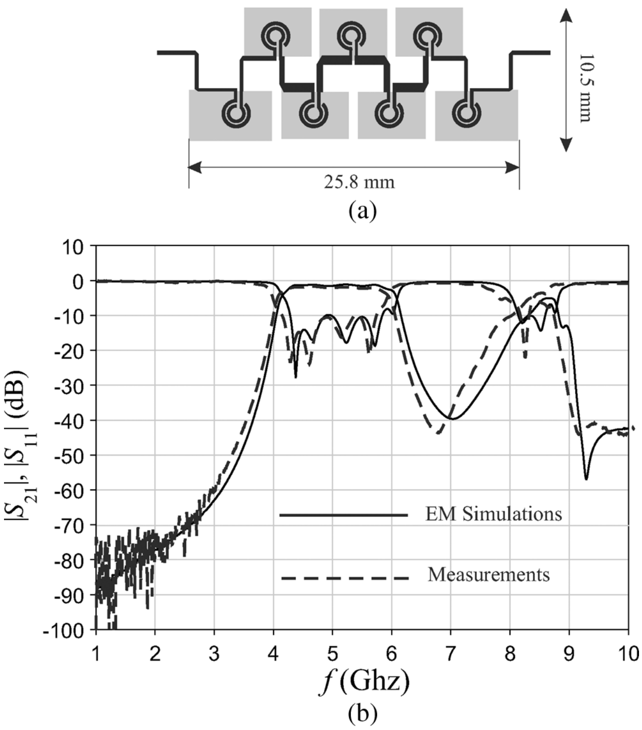


Fig. 5. (a) Layout of the designed filter using bend lines as inverters. (b) Measurements and EM simulations of the filter response.

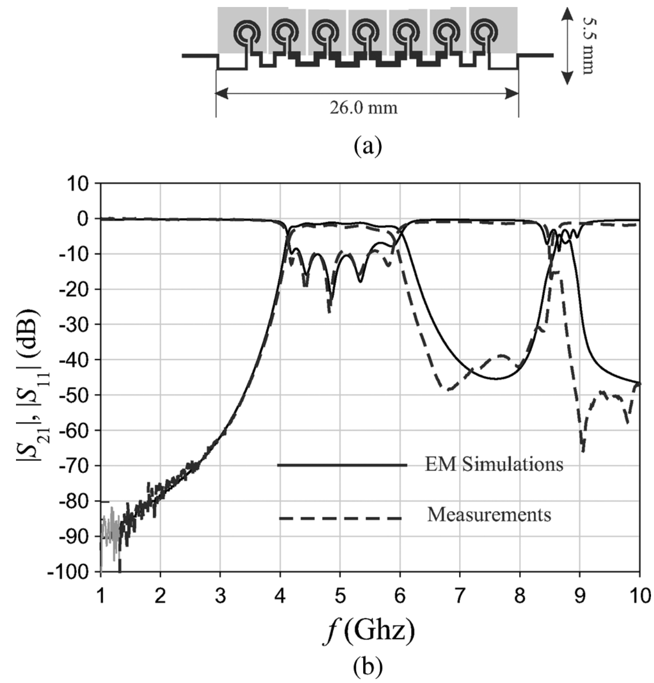


Fig. 6. (a) Layout of the designed filter using meander lines as inverters. (b) Measurements and EM simulations of the filter response.

cases, we have used the EM simulation to preserve the correct performance of the inverters. The layouts and responses of the filters are shown in Figs. 5 and 6. From Figs. 5(b) and 6(b) it can be concluded that the filter response is not meaningfully modified by the presence of bends and meander lines.

## IV. Conclusion

A wideband bandpass filter has been designed and implemented by using OSRRs (for size reduction) with full control on the filter specifications. The design is based on the use of $\lambda/4$ inverters with different characteristic impedances connecting identical OSRRs. Three prototypes have been fabricated (using as inverters straight, bent, or meandered lines). Very good agreement has been found for the filter responses between the results provided by the EM simulator and the measurements. The performance of the fabricated filters matches reasonably well that of the designed filter.

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