Miniaturization of a Filter-Antenna Device by Co-Design

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ABSTRACT This paper presents a novel miniaturization approach by co-designing together a filter and an antenna. Indeed, contrary to a classical filter-antenna design, which presents a 50 Ω transition between the filter and the antenna, the co-design methodology proposed in this paper will prove that both the antenna and the filter can be optimized on a complex impedance. For this impedance, different from 50 Ω, the antenna volume can be reduced by more than 50% while presenting a high radiation efficiency. Moreover, the filter performance will be optimized on complex impedance loads without being affected compared to a classical 50 Ω filter. This new approach will be detailed and compared to a classical one in order to validate the improvement achieved by this co-design methodology. Prototypes have been manufactured and measurements confirm the benefits observed during the design phase.

INDEX TERMS Miniature antenna, radiation efficiency, microwave filter, filter synthesis, high dielectric resonator.

I. INTRODUCTION

WIRELESS communication system development leads to an increasing demand on miniaturization and integration of microwave elements. Both filters and antennas are among the most important components of radiofrequency transmitters, and their dedicated volumes are directly related to their performances. Indeed, there are fundamental physical limits [1]–[3] constraining the miniaturization with the trade-off between performances, i.e., the radiation efficiency for an antenna and the quality factor for a filter, and their operating frequency and bandwidth.

In [4] and [5], a patch antenna is integrated with two bandpass filter networks consisting of one and two half-wavelength resonators, designed to excite two orthogonal modes with equal magnitude and quadrature phase. In this co-design approach, based on previous works [6], the patch antenna is treated as the last-stage resonator, i.e., as the output port of the filter network. In [7], multiple functions such as filtering, duplexing, and radiation are combined into one single device, leading to a simplified RF frontend. A co-designed antenna-filter is presented in [8]. It is composed of a microstrip patch antenna and a hairpin filter, sharing the same ground plane to reduce the size. Another example, presented in [9], is made of an inverted-L antenna working not only as a radiator but also as the last resonator of a bandpass filter. A design procedure is given, which clearly indicates the steps from the filter specifications to the implementation. A substrate integrated waveguide (SIW) filter-antenna device is presented in [10]. It consists of two cavity resonators with a slot antenna in the second cavity. The slot creates a third-order filtering response while preserving the radiating characteristics.

In this paper, the co-design approach will be driven by the main objectives of improving the efficiency of a filter-antenna device while having small dimensions. Previous works on the improvement of radiation efficiency of electrically small antennas have been presented in [11]–[12]. Indeed, a balanced miniature inverted-F-inspired circular antenna with a radius equals to λ₀/28 at 433 MHz and a 50% radiation efficiency is presented. In [13], we presented
a miniaturization technique of a monopolar wire patch antenna, while seeking to preserve its radiation efficiency.

In Section II of this paper, the co-design strategy where the 50 ohms interconnection constraint is released will be recalled. This strategy intends to miniaturize the overall system, and in particular the antenna by finding an optimal impedance ($Z_{opt}$) where the antenna will have high radiation performances while being electrically small.

In Section III, a miniaturization technique applied to a cavity filter structure allowing to keep significant quality factor and low insertion loss will be presented. For better miniaturization, a second order filter made with a high dielectric permittivity ceramic has been chosen. Moreover, to be highly miniaturized, capacitive effects are created thanks to the introduction of metallic post in the middle of each resonator. At this step, the miniaturization will be optimized by aiming for the best quality factor. The filter performance will be shown for an output impedance of 50 $\Omega$. However, in the frame of a co-design approach, we need to control the filter performance independently from the output impedance. Therefore, the effect of real and then complex loads on filter performances will be studied in the co-design approach detailed in Section V.

In Section IV, a study on the miniaturization of an antenna will be presented. This study is based on our previous paper [13] where we presented a methodology to keep the same radiation efficiency while miniaturizing an antenna. Indeed, an antenna with a reduced volume of more than 50% is optimized at 2.5 GHz on a particular impedance location, different from 50 $\Omega$.

Finally, Section V will merge results presented in Sections III and IV to present the co-design approach of a compact filter-antenna device working at 2.5 GHz, i.e., where the wavelength in free space equals 120 mm. The filter is expected with a selectivity constraint of 20 dB around $f_0 \pm 50$ MHz. Indeed, a 8-MHz passband working at 2.5 GHz with two poles is aimed for the filtering function.

In parallel, a filter antenna device with similar performances but developed considering a classical approach, i.e., both connected thanks to a 50 $\Omega$ transmission line, will be designed. A comparison between the co-design approach and the classical one in terms of radiating performances and overall dimensions will validate the interest of our proposed methodology. Filter-antenna prototypes are manufactured in order to carry out experimental measurements to confirm the simulation results concerning the benefits of the co-design strategy developed.

**II. PRESENTATION OF THE CO-DESIGN APPROACH**

In most of cases, antennas and filters are individually designed and connected by a 50 $\Omega$ transmission line or connector implying the global dimensions of the device to be large. Fig. 1 illustrates this classical approach.

The co-design approach assumes a direct point to point connection of the filter to the antenna releasing the real impedance constraint of 50 Ohms between the two components. The strategy followed aims to miniaturize the overall system, and in particular the antenna. Consequently, miniaturization techniques will be employed in order to find an optimal impedance ($Z_{opt}$) where the antenna will have high radiation performances while being electrically small. This approach is described in Fig. 2.

This approach will be detailed on a filter-antenna device working at 2.5 GHz, i.e., where the wavelength in free space equals 120 mm. The filter is expected with a selectivity constraint of 20 dB around $f_0 \pm 50$ MHz. Indeed, a 8-MHz passband working at 2.5 GHz with two poles is aimed for the filtering function.

In parallel, a filter antenna device with similar performances but developed considering a classical approach, i.e., both connected thanks to a 50 $\Omega$ transmission line, will be designed. A comparison between the co-design approach and the classical one in terms of radiating performances and overall dimensions will validate the interest of our proposed methodology. Filter-antenna prototypes are manufactured in order to carry out experimental measurements to confirm the simulation results concerning the benefits of the co-design strategy developed.

**III. MINIATURIZATION TECHNIQUE OF A SECOND ORDER CAVITY FILTER**

The initial structure of the filter is based on the two-pole filter design presented in [14]. The compactness is reached thanks to:

1) The use of a Zircona ceramic presenting a high relative permittivity ($\varepsilon_r = 33$) together with a low loss tangent ($\tan \delta = 9.210^{-4}$) not degrading the filter performances.
2) The insertion of a post in the middle of each resonator as depicted in Fig. 3.
Considering these miniaturization techniques, and respecting the initial specifications, the filter has been modeled with an electrical equivalent circuit and its parameters have been optimized (see Fig. 4).

Then, the structure has been modeled in 3D with an electromagnetic solver for dimensioning resonator and couplings in accordance with the optimized circuit parameters. S parameters obtained by circuit simulation and 3D electromagnetic (EM) simulation are compared in Fig. 5.

The working frequency equals 2.5 GHz and the insertion loss attains 4.2 dB. The good agreement between these simulations imply that both couplings and resonator dimensions have been well designed. In order to validate the filter performances, a prototype has been manufactured by the Centre for Technology Transfers in Ceramics (CTTC) [15], using a 3D ceramic manufacturing technology based on the principle of laser stereolithography (SLA). The metallic coating is obtained by electroless silver plating, and the thickness, which depends on the duration of the operation, is approximately 10 μm for these prototypes. The excitation and coupling patterns are laser etched and the silver conductivity has been evaluated at $\sigma = 1.5 \times 10^7$ S/m. Input and output couplings are sized appropriately with a GSG (Ground-Signal-Ground) probe for measurement. The accuracies achieved by the 3D ceramic manufacturing technology are 0.09 mm according to the z-axis and 0.2 mm according to the x- and y-axes. Measured performance is then compared with the previous simulation in Fig. 6.

A working frequency equals to 2.54 GHz with 5.1 dB insertion loss is measured. The slight difference between measurement and simulation can be explained by taking into account the actual dimensions of the filter. Indeed, measured dimensions presented in Fig. 7a are then integrated in the 3D electromagnetic simulator. This retro-simulation is compared to the measurement results in Fig. 7b, and a good agreement is now obtained.

IV. MINIATURIZATION OF AN ANTENNA WITH HIGH RADIATION PERFORMANCE

In [13], we developed two monopolar wire-patch antennas made with a Rogers RO4003 substrate (permittivity $\varepsilon_r = 3.55$ and loss tangent of $2.7 \times 10^{-3}$) on a 90 mm × 90 mm ground plane having the same radiation efficiency at 2.5 GHz:

1) The first one was matched on $50 \, \Omega$ and exhibited dimensions of $24 \, \text{mm} \times 24 \, \text{mm} \times 4 \, \text{mm}$ ($\lambda_0/5 \times \lambda_0/5 \times \lambda_0/30$ at 2.5 GHz) corresponding to a volume of 2304 mm$^3$. It is called the reference antenna.

2) The second one resulting of a geometry optimization had a reduced volume of more than 50%. This
antenna was optimized at 2.5 GHz on a particular impedance location while presenting a volume of 1024 mm³. It is called the miniature antenna.

Prototypes of the two antenna versions were manufactured (Fig. 8) and then characterized experimentally. The 90 mm × 90 mm ground plane has been added so that the effect of the antenna feeding coaxial cable on the measurement is negligible [16].

The Fig. 9 compares the measured and simulated input impedance of reference and miniature antennas. A good agreement between measurement and simulation is obtained and the input impedance value at 2.5 GHz can be deduced. For the reference antenna the input impedance is close to 50 Ω (targeted value during design) while it is equal to $Z_{\text{in}} = (9.5 - j36)$ Ω for the miniature antenna. Therefore, the $|S_{11}|$ parameter, presented in Fig. 10, shows that the reference antenna is well matched to 50 Ω around 2.5 GHz and the miniature antenna presents a poor matching of $-3.1$ dB.

Finally, the radiation efficiency has been evaluated both in measurement and simulation. Results are reminded in Fig. 11 and they constitute the most significant results of our previous paper [13]. Indeed, in our optimization process, the same radiation efficiency was kept at 2.5 GHz while dividing the antenna volume by two. In other words, we have shown that it is possible to optimize the radiation efficiency of this kind of antenna while miniaturizing its dimensions.

Therefore, an electrically small antenna with typical dimensions of $\lambda_0/7.5 \times \lambda_0/7.5 \times \lambda_0/30$ at 2.5 GHz, i.e., with a volume of 1023 mm³ exhibited a radiation efficiency equals to $-0.4$ dB. This efficiency value is the same than the one exhibited by a classical monopolar wire patch antenna matched on 50Ω but presenting larger dimensions equal to $\lambda_0/5 \times \lambda_0/5 \times \lambda_0/30$ at 2.5 GHz and corresponding to a volume of 2304 mm³. This issue of matching an antenna on a complex impedance rather than 50Ω for optimizing the radiation efficiency is the key of this paper since it will be solved with a co-design approach with the filter, presented in the next section.

V. CO-DESIGN OF THE FILTER-ANTENNA DEVICE

Within a co-design approach, both the filter and the antenna need to be matched on conjugate impedances. Based on studies presented in the previous sections, the first objective is to match the filter on the conjugate input impedance of the miniature antenna, i.e., on $Z_{\text{in}} = 9.5 - j36$. The next
A. INFLUENCE OF THE FILTER OUTPUT IMPEDANCE

The filter presented in Section III had a loaded quality factor of 85 and was designed considering input and output impedances of 50 Ω. In the co-design approach, the filter will be fed on its input with a 50 Ω SMA connector while its output will be connected to the antenna.

Considering the previous electrical equivalent circuit of the filter, the load is changed and now equal to different real impedances ranging from 5 Ω to 200 Ω. In this case, if the values of the couplings (input coupling, mutual coupling and output coupling) are kept, the S-parameters of the filter and thus the targeted specifications are modified. On the other hand, by re-adjusting the output coupling, it is possible to retrieve the performances of the filter loaded on 50 Ω as presented in Fig. 12.

Therefore, theoretically, no more losses are introduced in the system matched on different real impedances, i.e., the filter keeps its loaded quality factor of 85 regardless of the load impedance as long as it is real.

However, the input impedance of the miniature antenna is not just a real part since its input impedance equals $Z_{in} = (9.54 - j36) \, \Omega$. Therefore, the integration of a transmission line between the filter and the antenna will allow balancing the imaginary part while stacking the filter with the antenna.

Fig. 13 presents the equivalent electrical circuit of the global system.

In order to match the filter impedance, the output impedance $Z_{out}$ needs to be real. An electrical length of 36.5° for a 50 Ω characteristic impedance line is chosen such as $Z_{out}$ is real and equal to 6 Ω.

Finally, this line is integrated as a stripline within the 3D design as presented in Fig. 14.

The new input impedance of the subsystem combining the stripline and the antenna is evaluated using 3D electromagnetic simulation tool and presented in Fig. 15. As expected, it is close to 6 Ω since it is equal to (6.05 + j0.2) Ω at 2.5 GHz.

The classical design procedure is carried out with the reference antenna and the filter matched on 50Ω and performances of each design are compared in the next part.

B. FINAL DESIGNS: COMPARISON OF THE CO-DESIGN AND THE CLASSICAL APPROACHES

Exploded views of the final {filter-antenna} designs are presented in Fig. 16. They are composed of a SMA connector, the filter, the stripline and the monopolar wire-patch antenna and a ground plane of 90 mm × 90 mm.

For the reference antenna, i.e., for the classical design, the monopolar wire-patch antenna has dimensions of
FIGURE 17. Final filter designs: classical conception (a) and co-design approach (b).

FIGURE 18. Simulated $|S_{11}|$ parameters for the classical conception and the co-design approach.

FIGURE 19. Simulated total efficiencies for the classical conception and the co-design approach.

24 mm $\times$ 24 mm $\times$ 4 mm while the dimensions are 16 mm $\times$ 16 mm $\times$ 4 mm for the miniature antenna, i.e., for the co-design approach. Filters for both designs have same dimensions (16 mm $\times$ 16 mm $\times$ 4 mm), the only difference between these two filters is the output slot shape as presented in Fig. 17.

Fig. 18 and Fig. 19 show the simulated $|S_{11}|$ parameters and the total efficiency [17] respectively for the two design approaches.

As expected, they both present similar results in terms of impedance matching, bandwidth and maximum total efficiency. Indeed, the total efficiency of the two systems are almost the same and close to $-4.8$ dB at 2.5 GHz, corresponding to the sum of losses due to the filter (4.2 dB), the antenna (0.4 dB) and the stripline (0.2 dB).

Prototypes have been fabricated, in Zirconia, by using the stereolithography technique, for the filter and by classical printed circuit manufacturing using Rogers RO4003 for the stripline and the antenna. After the fabrication of the filter, its dimensions have been measured to anticipate a possible frequency shift as observed and shown in Section III. It appeared that there are some differences between post dimensions when compared the two filters implying that:

- The filter optimized on $Z_{in} = (9.5 - j36)$ $\Omega$ is working at 2.28 GHz.
- The filter optimized on 50 $\Omega$ is working at 2.52 GHz.

Therefore, striplines are adjusted considering these working frequencies. Finally, the filter and the antenna are assembled thanks to solder balls such as the output of filter is in front of the input of the stripline as presented in Fig. 20.

Final filter-antennas prototypes are presented in Fig. 21. The prototypes are measured, and their performances are compared to simulations, taking into account the actual
FIGURE 22. Comparison of the simulated and measured $|S_{11}|$ parameters for the classical conception and the co-design approach.

FIGURE 23. Comparison of the simulated and measured total efficiencies for the classical conception and the co-design approach.

TABLE 1. Dimensions and main performances of the final designs.

|                  | Classical design          | Co-design                |
|------------------|---------------------------|--------------------------|
| Working frequency band | [2.51–2.53] GHz          | [2.27–2.29] GHz          |
| Antennas dimensions | $\lambda/5\times\lambda/5\times\lambda/29.7$ at 2.52 GHz | $\lambda/8.2\times\lambda/8.2\times\lambda/32.9$ at 2.28 GHz |
| Antennas volume   | 2304 mm$^3$               | 1024 mm$^3$              |
| Maximum total efficiency | -5 dB / 31.6%            | -5 dB / 31.6%            |

dimensions of each filter. $|S_{11}|$ parameters are presented in Fig. 22.

This figure shows that both devices are well matched around 2.28 GHz for the co-design approach and around 2.52 GHz for the classical design. 3D radiation patterns are also measured within an anechoic chamber. From these measurements, one can deduct the total efficiencies with respect to the frequency, as presented in Fig. 23. Main performances and dimensions are summarized in Table 1.

These results are validating our co-design approach since the total efficiency is the same with a reduced volume. Therefore, by reducing the global dimensions of the radiating element by about 50% (volume), same level of total efficiency is reaching around the same frequency involving the reduction of its volume and electrical size.

Comparison of the measured and simulated efficiencies shows that the relative bandwidths of the measured efficiencies are slightly wider than predicted by the simulation. This can be explained by a possible misalignment between the filter and the antenna during manual assembly.

VI. CONCLUSION

A novel miniaturization approach by co-designing a filter and an antenna has been presented in this paper. Indeed, a 50 $\Omega$ transition between the filter and the antenna has been avoided to reduce the global volume of the device. A first step was to miniaturize a cavity filter structure while keeping a significant quality factor for low insertion loss. For sake of miniaturization, a second order filter combining a high dielectric permittivity ceramic with a capacitive effect created by the insertion of a post in the middle of each resonator has been employed. The filter performance is maintained even with a load different from 50 $\Omega$. In parallel, a study on the miniaturization of an antenna while keeping the same radiation efficiency has been reminded and shows that an antenna with a reduced volume of more than 50% can be optimized on a particular impedance locus different from 50 $\Omega$ while keeping the same radiation efficiency.

Finally, the co-design of a filter-antenna device without having a 50 $\Omega$ transition but an optimal complex impedance where both the antenna and the filter have high performances while having compact size has been presented. In order to validate the co-design methodology, the obtained performances have been compared with ones of a classically
designed filter-antenna device, i.e., with a 50 Ω transition between the filter and the antenna. Prototypes of filters, antennas and filter-antenna devices were manufactured and characterized experimentally. The measurement results confirm the simulated ones. The interest of co-design approach is validated since performances of both designs show that the total efficiency and filtering properties are the same while the sub-system obtained by co-design has reduced volume.

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