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# Varying the Operation Bandwidth of Metamaterial-Inspired Filtering Modules for Horn Antennas

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**Abstract**—Recently, we have presented a novel approach to design metamaterial-inspired notch filters that can be integrated within horn antennas of receiving systems to mitigate the effects of narrowband interfering signals. The filter module consists of a single Split Ring Resonator (SRR), whose rejection band needs to be matched to the bandwidth of the particular interfering signal we want to suppress. Extending our previous work, we show here how it is possible to control the bandwidth of such a filtering module by using different metamaterial-inspired resonators. In particular, we show that, while a reduction of the rejection band can be easily obtained by increasing the miniaturization rate of the resonator, the enlargement of the rejection band cannot be obtained in the same way by simply reducing the resonator quality factor. We show that a solution of the latter problem can be worked out by applying the "critical coupling" concept and considering the filtering module to be made of two equal SRRs with a proper optimal separation. The effectiveness of the approach is demonstrated trough proper full-wave simulations and experiments on a fabricated prototype. The proposed technique, used here to design a filtering module for a specific radiating system, has a more general relevance and can be applied to all cases where the operation bandwidth of a component is limited by the resonant nature of a single metamaterial-inspired particle.

## 1. INTRODUCTION

The term "metamaterial" refers to the wide range of artificially engineered materials, typically synthesized by arranging conductive structures of particular shape and size in a host dielectric medium. The electromagnetic parameters and geometry of such inclusions are designed to change the response of the host material and obtain special properties that are not achievable by conventional materials. Because of the inherent limitations associated with the physical realizability, a passive metamaterial must necessarily be dispersive in frequency [1]. Consequently, the desired properties are typically obtained only in a narrow frequency range. The same issue applies also in 2D artificial structures (e.g., metasurfaces and metamaterial transmission lines) or in structures consisting of single metallic inclusions (e.g., metamaterial inspired-structures) [2–10].

To overcome this limitation and achieve a broadband operation, the use of active inclusions has been proposed [11–13]. However, this solution significantly increases the complexity of the components and involves stability problems.

Recently, several metamaterial-inspired modules have been proposed by our group to design innovative radiating and transmitting components with a filtering behavior [5–10]. In these structures, the inherent narrowband operation of metamaterial resonators is advantageously exploited to reduce the otherwise large operation bandwidth of some components, enabling, thus, a filtering behavior on top of the regular operation of the component itself (e.g., polarization transformer or radiating element). Please

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note that other antennas and microwave components loaded with metamaterials have been proposed (see, for instance [14–16]). However, our approach is typically more simple and economic as it is based on the use of a single inclusion instead of a bulk metamaterial. In particular, in [7] a single split-ring resonator (SRR) has been placed at the throat of a pyramidal horn to add a notched-band inside the operation band of the antenna. However, when using such a radiating element in actual operating systems, we may want to be able to adjust the width of the rejection band, depending on the bandwidth of the particular signal to be filtered out.

The aim of this paper is to propose some solutions to this issue, showing how it is possible to narrow or broaden the operation bandwidth of the filtering structures made by metamaterial-inspired resonators. In particular, we show that, by using more miniaturized structures such as multiple split-ring resonators (MSRRs), we can reduce the notched band compared to the case of a single SRR. On the contrary, by using an inclusion with a reduced miniaturization rate (i.e., a larger inclusion), we show that the notched band can be broadened at the cost of dramatically affecting the performance of the component outside the notched-band. Finally, in order to solve this further issue and achieve broadband operation without affecting the out-of-band performance, we propose a new approach based on the "critical coupling" concept consisting in using two properly spaced identical resonators.

The structure of the paper is as follows. In Section 2, we present the design of self-filtering horn antennas with a single metamaterial-inspired resonator, comparing the bandwidth achieved by using different geometries of the particle. In Section 3, we extend the concept of "critical coupling" to the considered antenna configurations to enlarge the notched-band of the filtering module. In Section 4, we present the experimental measurements conducted on a fabricated prototype. Finally, the conclusions are drawn in Section 5.

## 2. DESIGN OF A HORN FILTENNA WITH A SINGLE METAMATERIAL-INSPIRED RESONATOR

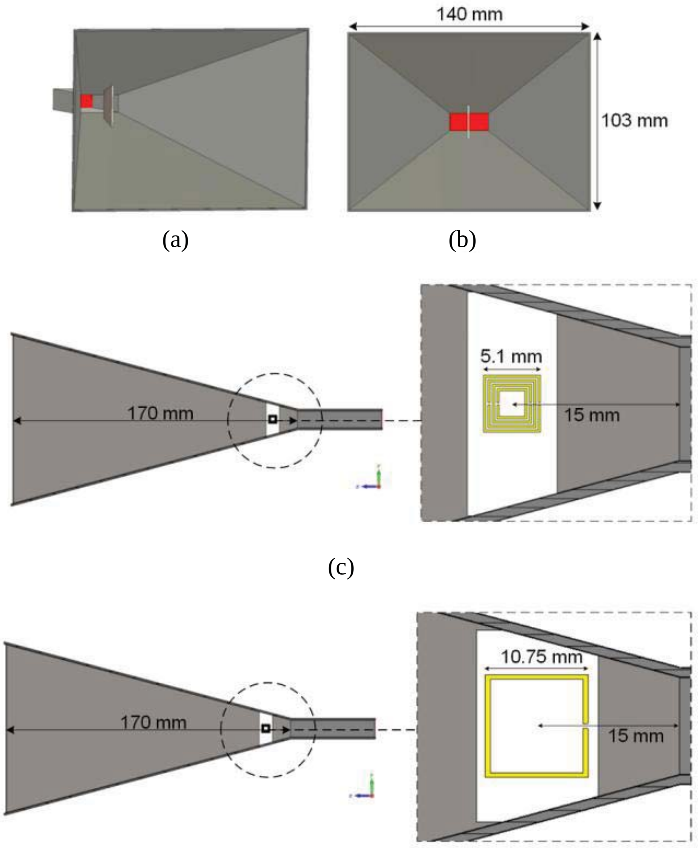
### 2.1. Overview of the Proposed Structures

Recently, we have presented some radiating elements that perform different manipulations on the transmitted/received signal [5–8, 17]. In particular, exploiting the strong magnetic resonance of a SRR, we have recently proposed a filtering horn antenna with band-stop characteristics. In this case, the resonant inclusion, placed within the throat of the horn, dramatically affects the impedance matching of the antenna around its resonant frequency, resulting in a narrow rejected band. However, due to the limited bandwidth of the SRR, this structure can be used only in specific receiving systems, in which the fractional bandwidth of the interfering signal approximately coincides with that of the chosen resonant particle.

To further reduce the operational bandwidth of the filtering module, we propose here to use a MSRR, which is a more compact version of the SRR. In fact, as shown in [18], by adding more internal rings to the SRR, we can reduce its resonant frequency, without increasing its overall dimensions. This result can be used to obtain a narrower bandwidth (compared to the one achieved by using a single SRR) around a fixed resonant frequency, simply by reducing the size of the particle and increasing the number of rings (see Figure 1(c)).

On the contrary, to broaden the bandwidth of the filtering module, a possible solution is to eliminate the inner ring of the SRR, obtaining, thus, a simple open-ring resonator (ORR). In fact, the inner ring is typically employed to increase the equivalent capacitance of the resonant inclusion, leading, thus, to a reduced resonant frequency. Removing the inner ring, thus, we reduce the quality factor of the resonator, increasing, thereby, the fractional bandwidth (see Figure 1(d)).

Please note that the position of the different inclusions inside the horn has been properly chosen, as explained in [7], to obtain an optimal behavior in terms of both rejection within the notched band and impedance matching outside the notched band. The dimensions of the resonant inclusions have been selected, instead, to obtain a resonant frequency around 10 GHz, in order to make a proper comparison with the results obtained in [7] with a single SRR. These dimensions have been chosen through a numerical optimization. However, these may also be calculated by using expressions similar to those reported in [18], as long as they consider the effect of the dielectric substrate on the equivalent circuit model [19]. In particular, the metallization and the capacitive gaps have a width of 0.2 mm in the case



(a) (b)

(c)

(d)

**Figure 1.** Geometrical sketch of the proposed horn antenna with different notched-band filters: (a) perspective view; (b) front view; (c) side view with MSRR; (d) side view with ORR.

of the MSRR, while they have a width of 0.5 mm in the case of the ORR. All the other dimensions are reported in Figure 1. In particular, the external dimensions of the MSRR and the ORR, equal to 5.1 and 10.75 mm, respectively, confirm the different miniaturization rates of the two resonators compared to the SRR used in [7]. The MSRR and the ORR are both etched on the same dielectric substrate (Roger DuroidTM RT5870 with $\varepsilon_r = 2.33$, $\tan\delta = 0.0012$ and thickness of 0.787 mm) used for the SRR and properly shaped in order to facilitate the placement of the filtering module inside the throat of the horn.

## 2.2. Simulation Results

In order to evaluate the performance of the different particles, a proper set of full-wave simulations has been carried out by using the transient solver of CST Microwave Studio [20]. In particular, assuming the filtering module proposed in [7] as the reference, we have simulated the behavior of the self-filtering horn antenna reported in Figure 1 with both the MSRR and the ORR. The effect of introducing the two different filtering modules has been evaluated in terms of the reflection coefficient amplitude and the realized gain of the antenna.

As shown in Figure 2, replacing the SRR with the MSRR, we obtain a narrower notched band and, with a proper positioning of the inclusion, it is also possible to obtain a good impedance matching without affecting the antenna performance outside the notched band. On the contrary, by using the ORR we obtain a larger stop-band due to the lower quality factor of the inclusion. However, the side effect of increasing the dimensions of the resonator is that the out-of-band performance worsens significantly.

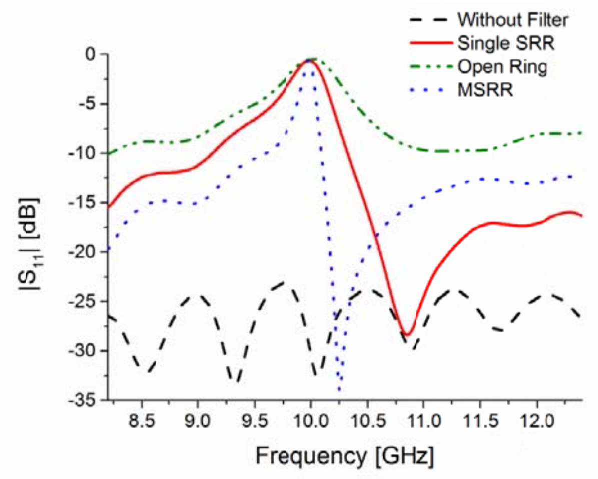


**Figure 2.** Simulated reflection coefficient amplitude at the input port of the horn with and without the different filtering modules considered.

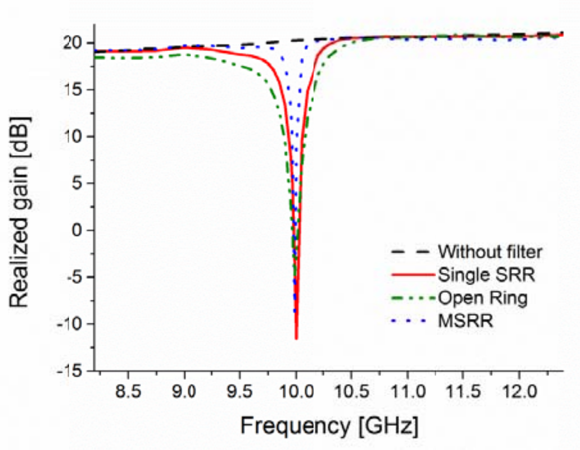


**Figure 3.** Simulated realized gain in the main beam direction of the horn with and without the different filtering modules considered.

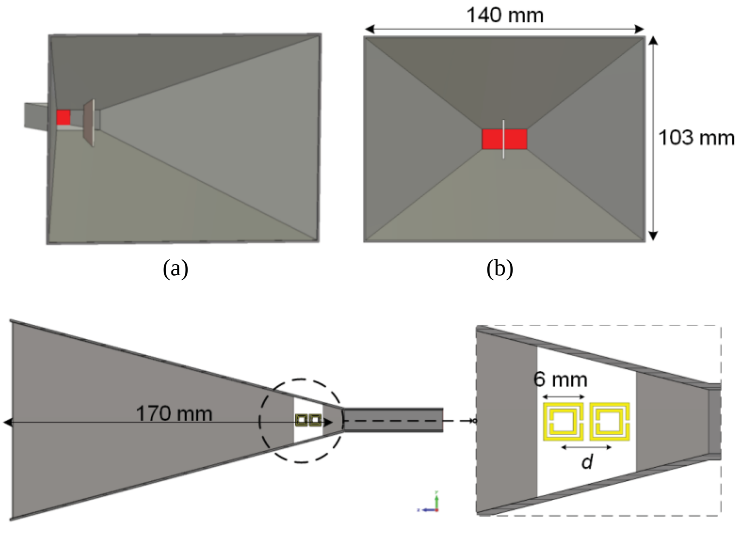
The aforementioned behavior of the two filtering modules is confirmed by the realized gain of the antenna in the main beam direction, shown in Figure 3. As expected, in fact, the realized gain in the case of the MSRR is very low within a narrower frequency band, compared to the case of the SRR. The use of the MSRR, thus, can be useful in the case of extremely narrow-band interfering signals. On the contrary, the use of an ORR, though allowing a slight enlargement of the notched-band, is not recommended since leads to an undesired significant reduction of the realized gain at low frequencies, compared to the one of the regular horn antenna. This result confirms that if we want to widen the notched-band we cannot simply play with the miniaturization rate of the inclusion. In order to overcome this limitation, we show in the following a new approach based on the use of two identical resonators, which, if appropriately coupled, allow enlarging the bandwidth without affecting the out-of-band performance.

## 3. DESIGN OF A HORN FILTENNA WITH COUPLED SRRS

Coupling between resonant LC circuits is widely used in circuit theory to achieve better performances or new degrees of freedom. For instance, two identical LC circuits (resonating at the same frequency $f_0$) can be capacitively coupled to obtain double-tuned circuit filters typically used in radio equipment. The same circuits can also be inductively coupled, as it happens for instance in the case of a two-coil system where the coil separation determines the coupling strength. In this latter case, different performances can be obtained depending on the distance between the two resonators [21]. In particular, if the coupling between the elements is too low (e.g., the distance between them is too large), the bandwidth of the overall system is larger compared to the one of a single circuit. However, this case, known as "under coupling", is not typically used because the power-transfer from one element to the other is inefficient. On the contrary, if the coupling is too strong (i.e., the distance between the elements is too short) the frequency response exhibits two peaks with a dip between them, which does not allow obtaining a broadband behavior. The optimal solution between these two extremes is the so-called "critical coupling" condition, corresponding to the highest possible power transfer and, at the same time, the maximum bandwidth in the frequency response.

Considering that the SRR is an electrically small resonator, the frequency response around its resonant frequency can be predicted by using an LC equivalent circuit, whose inductance and capacitance depend on the geometrical and electromagnetic parameters [18, 22] of the particle. Then, if we consider two identical SRRs, we can straightforwardly apply all the previous considerations about resonant circuits, including the "critical coupling" concept.

In particular, as shown in Figure 4, two equal SRRs, printed on the same substrate used in the



(a) (b)

(c)

**Figure 4.** Geometrical sketch of the proposed horn antenna with the coupled SRRs: (a) perspective view; (b) front view; (c) side view.

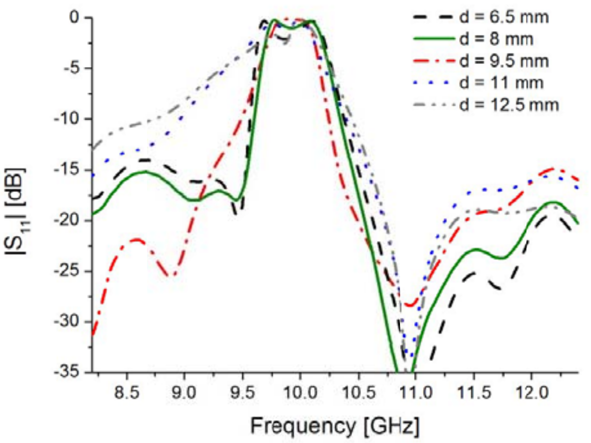


**Figure 5.** Simulated reflection coefficient amplitude of the horn filtenna with coupled SRRs for different values of the distance $d$ between the resonators.

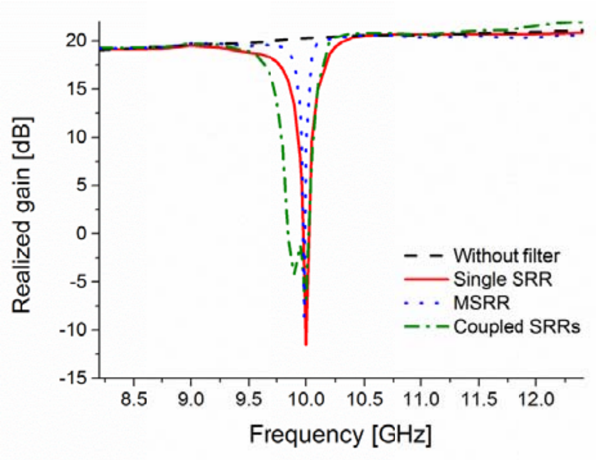
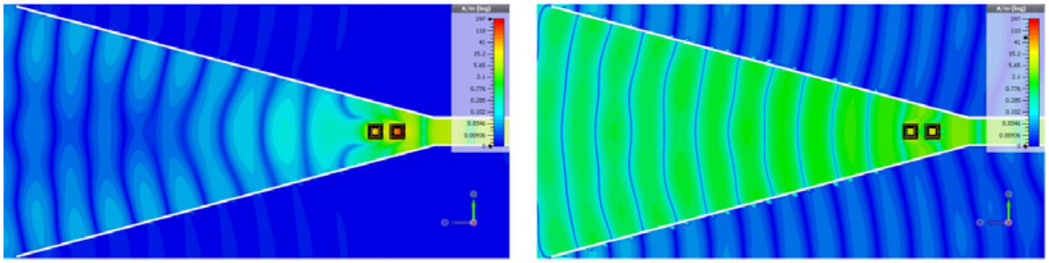


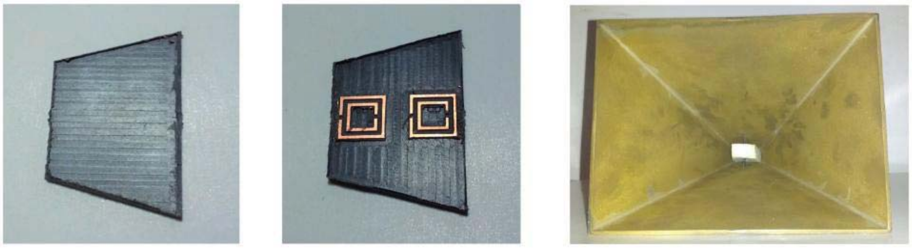
**Figure 6.** Simulated realized gain in the main beam direction of the horn with the coupled SRRs and of the horn with the the different filtering modules consisting of a single metamaterial-inspired inclusion.

examples reported in the previous Section, have been placed at the throat of the horn. In order to determine the "critical coupling" condition, we did vary the distance $d$ between them. As shown in Figure 5, for $d = 9.5\,\mathrm{mm}$, we obtain an optimal behavior with a flat shape of the reflection coefficient amplitude within the rejected band and the largest notched band. Moving $d$ away from the optimal value, the reflection coefficient amplitude exhibits two peaks with a deep between them, while the impedance matching at the lower frequency band is deteriorated when increasing $d$. From this plot it is clear that inserting a second SRR inside the throat of a regular horn, a wider rejection band can be obtained. The realized gain, reported in Figure 6, confirms this result, showing a wider minimum around 10 GHz. In particular, considering a 0 dB reference value, the coupled resonators allow obtaining a notched band that is around 3.7 and 15 times larger than the one of a single SRR and MSRR, respectively. Finally,



(a) (b)

**Figure 7.** Simulated absolute value of the $H$ field on the plane of the SRRs at (a) 10 GHz and (b) 11 GHz.



(a) (b) (c)

**Figure 8.** Photographs showing: (a) bottom and (b) top views of the realized coupled SRRs; (c) the filtering module fixed in the horn antenna.

in Figure 7 we have reported the absolute value of the $H$ field on the plane of the SRRs at 10 GHz (inside the notched band) and 11 GHz (outside the notched band). From these figures, we can see that inside the notched band the electromagnetic field propagating inside the horn highly interacts with the SRRs leading to a strong reduction of the electromagnetic field that propagates beyond them. On the contrary, at 11 GHz, the electromagnetic field is almost completely unperturbed despite the presence of the SRRs.

Please note that the application of the proposed solution is not limited to the components considered here but can also be exploited in other metamaterial-inspired structures based on the use of electrically small resonators [23, 24].

## 4. MEASUREMENTS

As shown in the previous section, the use of two identical SRRs allows widening the bandwidth of a metamaterial-inspired notch filter. To experimentally validate this result, the coupled SRRs in the configuration reported in Figure 4 have been manufactured by using a LPKF Protomat-S milling machine. Then, a prototype of the overall structure (antenna + filter) has been assembled and experiments were carried out to measure the antenna performance. A photograph of the assembled structure and its elements is shown in Figure 8. Please note that the filtering module has been fixed inside the horn by using a small foam block that does not affect the performance of the overall structure.

First, we have measured the reflection coefficient amplitude at the input port, which is in a good agreement with the simulations (see Figure 9). In particular, although there is a slight shift in frequency due to a positioning error of the filtering module along the $x$-axis (around 0.5 mm, according to a proper set of full-wave simulations), the antenna exhibits the required broadband rejection at around 10 GHz, while it is well matched in the rest of the frequency band of operation. Then, we have measured the transmission performances between two identical horn antennas with and without the filtering inclusions. These results, shown in Figure 10, confirm that by using two critically coupled SRRs, we are able to achieve the desired broader rejection band.

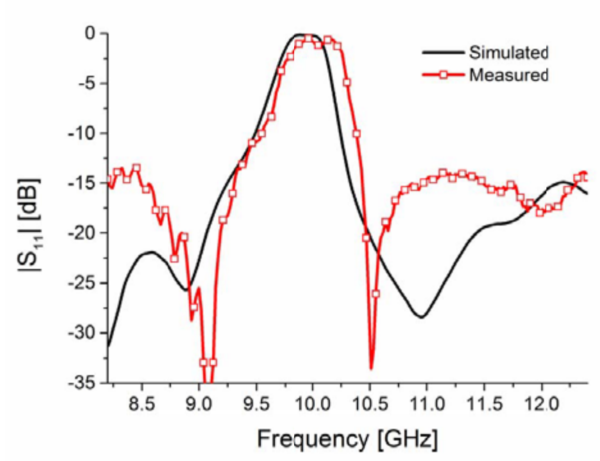


**Figure 9.** Simulated and measured reflection coefficient amplitude at the input port of the horn filtenna with coupled SRRs.

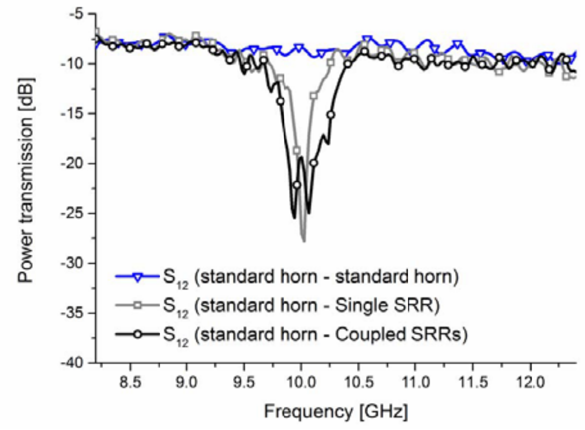


**Figure 10.** Power transmission between two standard horns, between two standard horns both loaded with single-SRRs [6], and between two standard horns with the coupled-SRRs shown in Figure 9.

## 5. CONCLUSION

In this communication, we have first shown how to reduce/increase the operation bandwidth of metamaterial-inspired filtering modules integrated in horn antennas by changing the geometry of the resonator. From the full-wave simulations it can be seen that we can reduce the rejection band by using more miniaturized inclusions with respect to the SRR. On the contrary, we have found that it is not possible to broaden the rejection band in a similar manner without affecting the performance of the horn outside the stop-band. Then, we have shown that by using two SRRs with equal dimensions, we can exploit the mutual coupling between them to obtain a larger rejection band than normally available with a single SRR. This approach, inspired by the "critical coupling" between resonant circuits, allows obtaining a rejection band that is around 3.7 times larger than that of the single SRR. Finally, we have fabricated a prototype of the antenna loaded with the coupled resonators and tested the corresponding filtering antenna. Both matching and radiating properties confirm the expectations.

We remark here that the proposed solution can also be employed to enlarge the inherent narrow bandwidth of other components based on the use of single metamaterial-inspired resonators, which typically represents their main limitation.

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