TAILORED METAMATERIAL-BASED ABSORBERS FOR HIGH ORDER MODE DAMPING

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Abstract

In modern particle accelerators, satisfying the desired beam properties (high currents, high luminosities, etc) increasingly implies limiting the total beam coupling impedance, which depends on the machine and the parameters of the circulating beams. A number of different reduction techniques have been proposed during the years depending on the specific applications, ranging from higher order modes (HOM) damping to solutions entailing high electrical-conductivity coatings of the pipe. This paper investigates the use of metamaterial-based absorbers for sensibly reducing or nearly cancelling the HOM contribution to the impedance. We design and fabricate sub-wavelength two-dimensional metallic resonant structures based on the split ring resonator (SRR) geometry that can be employed as mode dampers in accelerating structures. Experimental results inside a pillbox cavity well agree with full wave electromagnetic simulations. In this work we present the first results on a SRR geometry tailored for LHC collimators. We showed how metamaterials can be a valid alternative for impedance mitigation in experimental devices commonly operating along a particle beam line.

INTRODUCTION

The last generation accelerators require high quality beams with larger beam currents and luminosity values than what is currently achievable. To fulfill these requirements, beam instabilities must be avoided and/or limited optimizing machine parameters and studying the particle dynamics [1]. An important parameter for the study of the forces acting on beam is the beam-coupling impedance. It is defined as the integral over the normalized Fourier transform of the electro-magnetic (EM) force along the particle trajectory [2].

Following this definition, the impedance value depends on the surrounding chamber and on the beam velocity only [3]. The complexity of the vacuum vessel, with different cross-section variations due to the presence of several components and the diversity of constituent materials, gives different adding contributions to the total machine impedance [3]. In most cases, the discontinuities in the geometry behave like resonant (parasitic) cavities, where higher order modes (HOMs), excited by the travelling beam, may remain trapped increasing the total machine impedance and leading to excessive power losses. The use of HOM suppressors is crucial to mitigate the coupling impedance growing, to preserve the beam dynamics and reduce the relevant heat load. Each of these modes is described by a specific quality factor Q, a resonance frequency f_{res} and a shunt impedance R_{sh} [4]. Techniques oriented at the reduction of R_{sh} and/or Q are commonly referred to as mode damping strategies. In real cavities, HOM-removal mechanisms can be realized using external waveguides [5], unconventional resonant dielectric [6] or hybrid (metallo-dielectric) [7, 8] structures. In parasitic cavities, conventional approaches more often entail the use of dispersive or resistive materials acting as microwave absorbers when placed in specific points of the structure itself. Our work explores the possible use of metamaterials as an alternative and efficient mode damping strategy to be exploited for the improvement of the beam quality in future accelerators. Metamaterials are artificial materials acquiring their properties from geometry rather than composition, using inclusions or small inhomogeneities as "meta-atoms" to produce an effective macroscopic behaviour. They are generally comprised of sub-wavelength metallic elements in periodic patterns and are proving to be capable to achieve control over reflection, absorption, and propagation of EM waves by geometry only and in a wide frequency range by combing devices of different geometries [9]. Moreover, since they usually possess inherently resonant features, metamaterials have been widely used in the past for the development of filters with a large out-of-band signal rejection [10]. In this context, metamaterials can be designed and tailored in order to specifically address the features of single accelerator components. Very recently, metamaterial structures have been also proposed for the development of high-power, high-gradient wakefield accelerators [11].

The present work aims to investigate the use of periodic arrays based on simple split-ring resonators (SRR) [12], which stand out for simplicity amongst other designs, as possible beam coupling impedance reducer devices. The insertion in particle accelerators of SRR-based metamaterials has already been theoretically studied, showing their impact on resistive-wall impedance both longitudinally and transversely [13]. Their impact on the electromagnetic response of a well known resonant structure, a pill-box cavity, has been numerically investigated and experimentally measured [14]. Starting from the results of our previous analysis, in the present work we explore SRR configurations to be located inside LHC collimators as ad-hoc resonant mode dampers.

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SPLIT RING RESONATORS IN PILLBOX CAVITY

SRRs are commonly used as unit cells of a periodic array formed by one or more concentric structures, each one interrupted by a gap (see Fig. 1(a)). When exposed to an external electromagnetic field, they have an inherently resonant response, which strongly depends on their dimensions. Due to the gap presence, dimensions of the SRRs are much lower than those of structures without gap and resonating at the same frequency [9]. The assembling of two or more rings in a row or in an array induces a coupling between adjacent "meta-atoms," which depends on their relative distance and orientation (see Fig. 1(b)). This coupling influences the intrinsic resonances by varying the Q-factor and/or the frequency values. The collective behavior is, therefore, a function of their dimensions and geometrical arrangement [15, 16].

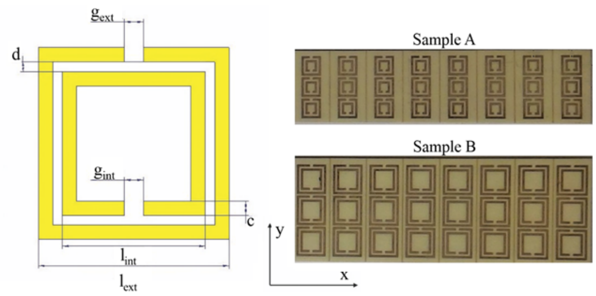

Figure 1: (a) Sketch of the metamaterial unit cell, consisting of a double square SRR ("meta-atom"). (b) SRR-based two-dimensional metamaterials realized on Alumina.

As a case study, we used an aluminum cylindrical pillbox cavity (see Fig. 2), which is well known from an analytical point of view. Due to the cylindrical symmetry of the pillbox, the mode contribution to the coupling impedance is given by the electric-field component along the cavity axis [17]. Therefore, in the following, we will focus on transverse magnetic (TM) modes only.

The analysis reported in this paragraph summarizes the work done in [14] and is useful as an introduction to what is described in the following paragraph.

In order to study the SRR impact on the pill-box EM response, we loaded the cavity with a metamaterial based on unit cells consisting of a thin (<5 μm) metallic layer having a squared double SRR strip geometry on polycrystalline Al2O3 (Alumina), with thickness 0.5. Structures based on them can then be easily realized in the microwave region using a standard PCB technology or any other lithography process.

Two-dimensional periodic SRR arrays have been fabricated having outer dimensions l_{ext} very similar, 5 mm and 8 mm for samples A and B respectively, see Fig. 1(b). The SRR dimensions and geometrical arrangements have been chosen so that the metamaterial intrinsic operational frequency and the SRR array stop-band lay in the 1-5GHz band where the first TM modes of the pill-box cavity are clearly visible. This choice maximizes the SRR effect on the working resonances of the accelerating structure [18]. Complete parameters of the two investigated metamaterials are reported in [14].

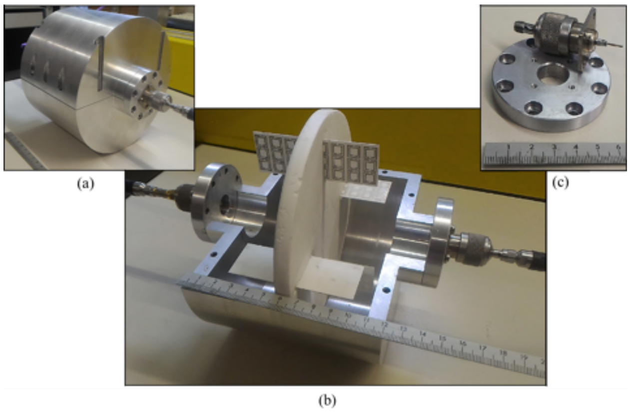

Figure 2: (a) The cylindrical pillbox cavity. (b) Open view of the SRR loaded cavity, where the input and output ports are shown. (c) Detail of the measurement antennas.

The commercial code CST Microwave Studio™ has been used to study the EM behavior of both the pillbox cavity and the SRR-based structures. Specifically: (i) Eigenmode solver for the evaluation of the pillbox resonant modes and field distributions, (ii) Frequency and Time domain solvers for the analysis of the scattering parameters of single and coupled SRRs first, and then cavity without and with metamaterial absorbers. The EM behaviour of single and coupled SRRs arranged in a planar array has been studied evaluating their reflection response to a plane wave incident along the y-direction with the magnetic field perpendicular to the ring plane and the electric field polarized along the direction parallel to the gap-bearing sides. This configuration has been chosen in order to have an EM field distribution similar to the one excited in the pill-box cavity used for the measurements (TM mode, see below).

Table 1: Single SRR resonance frequency f_{res}, stop-band (SB) array (3×8) and amplitude A_s from simulated S_{21} parameters.

Sample	A	B
f_{res} SRR (GHz)	4.40	2.10
SB SRR (GHz)	4.18-4.39	2.01-2.28
A_s SRR (dB)	−18.6	−21.4
A_s array (dB)	−26.0	−35.0

The resonance frequency of single SRR, the stop-band (SB) for the arrays and the corresponding amplitude minima A_s are calculated by means of full-wave analysis, looking at the scattering transmission parameter (S_{21}). Values are reported in Table 1. When compared to the corresponding single SRR, the main effect of the collective behaviour in each array is the appearance of a clear stop band, with multiple resonances starting at lower frequencies, and an increase in the power absorption testified by the larger A_s values.

The cylindrical pillbox cavity used for the experimental analysis and loaded with the SRR arrays is shown in Fig. 2, with details of the input and output beam pipes and the antennas. It works in the range 1-5 GHz and the first five TM modes are the TM_{010}, TM_{011}, TM_{012}, TM_{020}, TM_{021}, which resonate at 1.54 GHz, 2.16 GHz, 3.38 GHz, 3.56 GHz and 3.89 GHz respectively [14]. Four identical arrays of SRRs are placed on a rigid support (made of Rohacell®), spaced by $\pi/2$ in azimuthal angle, with the SRR plane perpendicularly oriented with respect to the magnetic field and facing the lateral cavity wall at a distance of 10 mm. In the following text, the term "empty cavity" stands for the pillbox with the rigid support only.

The effect of metamaterial insertion on the EM response of the pillbox cavity has been measured looking at the scattering transmission and reflection parameters, S_{21} and S_{11} respectively. A 2-port Vector Network Analyser (VNA) Rohde & Schwarz ZNB 20 has been used in the frequency range between 1 and 5 GHz.

In Fig. 3, the measured S_{21} parameter of the empty cavity is compared with the case loaded with the sample A, whose damping effect is clearly visible on the TM_{021} resonance peak. The measured behaviour of the SRR-array in the cavity is in agreement with its foreseen transmission spectrum as shown in the same figure by the simulated S_{21} curve in red. A clear lack in the transmission response of the stand-alone metamaterial is visible in correspondence of its working band [19].

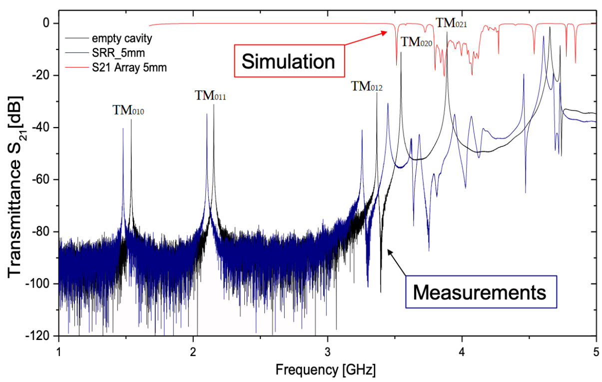

Figure 3: Measured S_{21} transmission parameter of the empty pillbox cavity (black curve) and of the loaded with sample A (blue curve). The red curve shows the simulated S_{21} response of the stand-alone SRR array.

For both SRR array samples in Fig. 4, a rigid shift towards lower values is clearly observed for all the resonance frequencies of the TM cavity modes. The effect is larger than the one given by the mere insertion of the dielectric substrates. Experimental data shows a change in frequency that goes from 2% to 8% in percentage. A "disruption" effect is visible in the spectrum (and highlighted in the squared box), where the intrinsic frequency bandwidth of the SRR

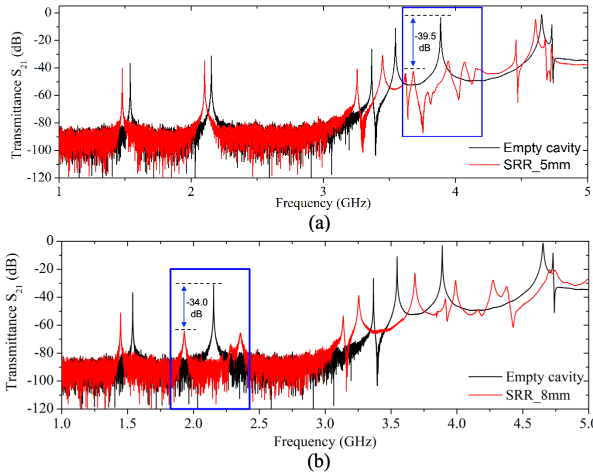

Figure 4: S_{21} transmission parameter of the empty pillbox cavity (black curve), compared with the cavity loaded with the SRR-based metamaterial, (a) sample A (red curve), (b) sample B (red curve).

array overlaps a resonance of the empty cavity. Indeed, for both samples, the corresponding cavity resonance is damped and red-shifted as expected from electromagnetic simulations. In the cavity loaded with sample B (see Fig. 4(b)), the TM_{011} mode decreases in amplitude (−34 dB), resonating now at 1.93 GHz. At the empty cavity design frequency (@2.15 GHz), the transmitted signal lies in the noise level, with an overall amplitude reduction of −53 dB. The same behaviour occurs for the TM_{021} mode inserting sample A in the pillbox (−39.5 dB amplitude reduction and red shift to 3.68 GHz). Correspondingly, the signal level for the intrinsic mode drops to −47.5 dB @3.9 GHz, as shown in Fig. 4(a). Moreover, it is evident that sample B has a minor effect on the TM_{021} mode too, since at that frequency the intrinsic SRR second order harmonic comes into play.

A comparative analysis of the empty and loaded cavity EM field mode distributions for some resonant modes is reported in [14]. This analysis demonstrated that far from their intrinsic frequency stop-band, SRRs have no influence on mode damping and the field mode patterns remain the same as its amplitude. However, approaching the SRR resonance region their influence is clearly visible. It is worthwhile to observe that the loss mechanism produced by the SRR array critically depends on the mode distribution [20] and consequently on metamaterial relative position inside the pillbox cavity.

Finally, we estimated the variation of the R_{sh} values for the empty and loaded (with both samples A and B) pillbox cavity in correspondence of the TM_{010}, TM_{011}, and TM_{021} modes by using the simulated R_{sh}/Q ratios and resorting to the measured quality factors Q [14]. As expected, the insertion of the SRR array sample A (B) drastically reduces the shunt impedance, and the coupling impedance, for the mode TM_{021} (TM_{011}) by a factor 10^2 (2×10^1). On the contrary, for the first TM_{010} mode the shunt impedance is almost unchanged.

TAILORED SPLIT RING RESONATORS IN LHC COLLIMATOR

Analysis done on a resonant cavity loaded with SRR arrays confirmed the possibility to damp specific cavity modes with metamaterials, so reducing the shunt impedance. Our studies showed how this loss mechanism critically depends on the resonator mode distribution. Next step has been the study of a possible use of this methodology in a real accelerator element: LHC collimators which are among the main contributors to the accelerator impedance. In this case the impedance exhibits many resonant peaks in a wide frequency range, between a few hundred MHz and 3 GHz [21]. Parasitic HOMs are created in the collimator tank, trapped between the sliding contacts as shown in Fig. 5. This is the slot region where ferrite blocks are normally located to damp HOMs. We studied mode distributions in this region performing CST simulations of a simplified collimator structure. For most modes the E-field is orthogonal to the slot, as in the example shown in Fig. 5(a) at 0.542 GHz. The H-field is parallel to the slot plane along the two orthogonal directions depending on the selected mode, see Fig. 5(b) at 0.542 GHz and Fig. 5(c) at 0.889 GHz.

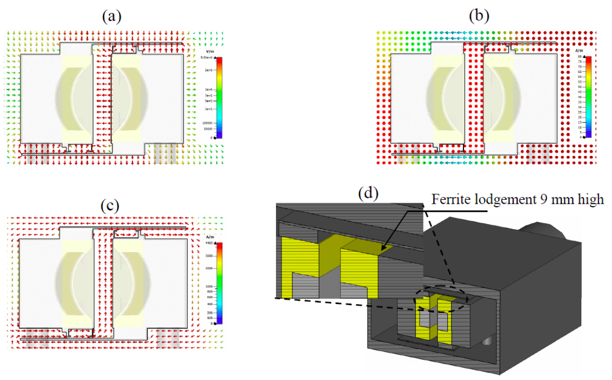

Figure 5: LHC collimator: simulation of (a) electric field at 0.542 GHz and of (b) and (c) magnetic field, at 0.542 GHz and 0.889 GHz respectively, distribution of different modes inside the structure. (d) Sketch of the section view highlighting the ferrite housing.

For the choice of right metamaterial, we have to keep in mind some constraints: the collimator geometry, the mode field distribution, the required operating frequency and the SRR working condition (H-field orthogonal to the ring area and E-field parallel to the ring gap). To fit all these requirements and guarantee a strong absorption response with a quite large bandwidth, we studied several SRR array samples working on ring geometry, their coupling and dielectric substrate.

Changing the substrate from Alumina to SL390 (a Kyocera type of ceramics with $\epsilon = 40$) and using a "Twin" configuration with no spacing between SRR, we obtained a larger bandwidth with a stronger response at lower frequencies without enlarging the ring dimension. The presence of a collimator trapped mode at around 0.2 GHz required to further extend the SRR electrical path. To this scope we analysed the behaviour of an inclined slab which allowed to further increase the rectangle small side length (see Fig. 6(a)). The simulated transmittance response of an SRR Twin sample is shown in Fig. 6(b). The metamaterial structure consists of two parallel arrays with long side length equal to 40 mm and 50 mm respectively, the same short side (20 mm) and inclined at an angle of 25°. A multi-band response, suitable for damping, is clearly visible in the range 0.2 – 0.35 GHz and at 0.42 – 0.53 GHz. Further studies of larger arrays with different lengths and coupling are under study in order to design an optimized metamaterial structure inside a real collimator.

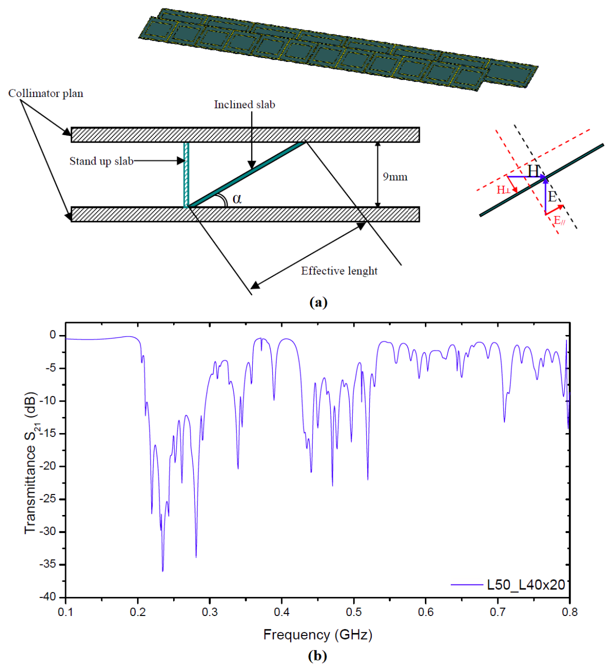

Figure 6: (a) A sketch of the "inclined" Twin configuration chosen for the SRR slab; (b) simulated transmittance at an angle of 25° with L_{S1} = 50 mm, L_{S2} = 40 mm, and W = 20 mm.

CONCLUSION

The present work investigated the introduction of novel mode damping strategies based on metamaterials for the reduction of the coupling impedance between particles and vacuum pipe environment. Simulations and measurements performed on SRR-based structures inside a simple pillbox cavity show their potential use as single mode dampers in a wide frequency range.

We proved that the reduction of R_{sh} and/or Q in resonant modes might be done through the insertion of tailored metamaterials acting as absorbers in specific positions inside the resonant cavities or, in general, in other critical components of an accelerating machine.

In this paper we proposed the use of a new configuration of SRR arrays (Twin structure) which can be easily adapted to different accelerator device geometries and mode distributions, as in the case of an LHC TCT collimator. A multi-band absorption response can be obtained using different size ring arrays. Furthermore, they can be easily positioned in the collimator using a smaller space with respect to ferrite.

Further studies, on the heat load and thermal response, also using different dielectric materials, of the Twin configuration inside real collimators are required to confirm our proposal.

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