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Reduction of the beam-coupling impedance in accelerating structures using metamaterial-based absorbers

M. R. Masullo[1], A Pugliese[1], N. Chikhi[1], V. G. Vaccaro[1], R. Losito[2], A. Masi[2], C. Koral[3], G. P. Papari[3], and A. Andreone[3]

[1] I.N.F.N. Naples Unit, via Cinthia, I-80126, Naples, Italy
[2] European Organization of Nuclear Research (CERN), Engineering Department, 1211 Geneva, Switzerland
[3] University of Naples "Federico II", Physics Department, Piazzale Tecchio 80, I-80125, Naples, Italy
masullo@na.infn.it

Abstract – Resistive-wall impedance constitutes a significant percentage of the total beam-coupling impedance budget of an accelerator. Under extreme conditions, like large power handling and ultra-high vacuum, metamaterial-based absorbers can represent a valid alternative to other approaches for impedance mitigation in specific accelerator components, like resonant (parasitic) cavities or collimators operating along the beam line. We design sub-wavelength 2D metallic resonant structures based on split rings or on 3D hyperbolic tapered waveguide arrays that can be employed as mode dampers in accelerating structures. A number of prototypes are fabricated and then measured in a "test model" pillbox cavity.

I. INTRODUCTION

A particle beam travelling in a vacuum tube experiences electromagnetic interactions with the surrounding environment, depending on the pipe shape and its constituent materials, which can be expressed through the concept of beam-coupling impedance [1]. A beam pipe is in fact characterized by many geometrical variations along the accelerator path, due to the presence of several components necessary for a proper operation: accelerating modules, collimators, diagnostic devices, test chambers and so on. Some of them have a very complex mechanical design with metallic movable materials, rf contacts, etc., to ensure their functionality. Each component usually gives a contribution to the total machine impedance and potentially contributes in destabilizing the beam [2]. In most cases, such discontinuities in the geometry behave like resonant (parasitic) cavities. The beam dynamics inside these "cavities" causes the excitation of undesired modes which can remain trapped and therefore can be described using a specific quality factor Q, resonance frequency f_0 and shunt impedance R_{sh} [3]. This last quantity is directly connected to the beam-coupling impedance of the mode. Techniques oriented at the reduction of R_{sh} and/or Q are commonly referred to as mode damping strategies, often entailing dispersive or resistive materials acting as absorbers when placed in specific points of the structure itself. At the same time, a complete damping strategy has also to take into account the contribution to beam instabilities due to the broadband impedance of specific components installed on the beam pipe.

This work explores the possible use of metamaterials as alternative and efficient mode damping strategy to be exploited for the improvement of the beam quality in future accelerators, since they can be designed and tailored in order to specifically address the features of the single components.

As possible beam impedance reducer devices, we investigate two different configurations: (i) periodic arrays based on split-ring resonators (SRR), which stand out among other structures for their simplicity, and (ii) hyperbolic metamaterials (HMM) consisting of metal-dielectric multilayers. In the former case the absorption process is based on the strong resonant behaviour of SRRs [4], and the resulting bandwidth is extremely narrow. In the latter, the response is ultra-wideband, polarisation insensitive, and wide angle, since the e.m. properties are based on the coupling of tapered waveguide modes operating at neighbouring frequencies [5].

Our work is inserted in the impedance studies on LHC collimators, which gave a large impedance contribution in the frequency range between hundreds of MHz to 3-4 GHz. For this reason, in order to study the effect of metamaterial-based absorbers on resonant structures, we decided to start our analysis on a standard pillbox cavity operating in the range between 1 GHz and 5 GHz.

In the following, we will present mostly, first numerically and then experimentally, the impact of different SRR periodic structures on the electromagnetic response of the resonant cavity. Preliminary results on

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hyperbolic metamaterial tapered waveguides, operating as broadband absorbers in the microwave region, will be also presented during the conference.

II. Metamaterial Design and Fabrication

SRR are commonly used as unit cells in different metamaterials and are formed by one or more concentric structures, each one interrupted by a gap, having an inherently resonant response when exposed to an external electromagnetic field. Due to the gap presence, dimensions of the SRRs are much lower than those of structures without gap resonating at the same frequency [4]. For this study, we designed a metamaterial based on unit cells consisting of a thin (~ 5 μm) metallic layer having a squared double SRR geometry on polycrystalline Al_2O_3 (Alumina) or G10 fiberglass laminates readily available from PCB industry, with thickness of 0.5 and 0.25 mm respectively. Such structure can be easily scaled at different frequencies in the microwave region using a standard optical lithography. Samples are shown in Fig. 1, left: (a) and (b) are fabricated on Alumina, (c) on G10. P_x and P_y represent the lattice parameters along x and y directions respectively. SRR unit cell dimensions are chosen in order to have samples resonating at different frequencies, with outer size very similar since they must match the pillbox cavity constraints. Electrical and geometrical parameters of the fabricated samples are reported in the table in Fig. 1, on the right.

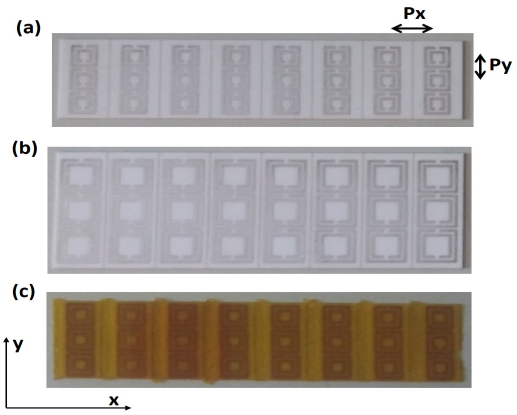

Fig. 1. Left: SRR-based two-dimensional metamaterials realized on Al_2O_3 substrate ((a) and (b)) and G10 fiberglass laminate (c). Right: Electrical and geometrical parameters of the SRR absorbers shown in the picture. ε_r and tanδ refer to the substrate dielectric constant and loss tangent respectively @1 GHz. P_x and P_y are expressed in mm.

The commercial code CST Microwave StudioTM has been used to study the EM behavior of both the pillbox cavity and the SRR-based structures. Specifically, Eigenmode solver for the evaluation of the pill-box frequency and field distribution, Frequency and Time domain solvers for the analysis of the scattering parameters of single and coupled SRRs first and of the cavity without and with metamaterial absorbers then.

In order to evaluate the effect of metamaterial insertion on the electrodynamics of the model cavity, we placed, in our simulations, 4 arrays of SRRs along the cavity axis spaced by $\pi/2$ in azimuthal angle and with their plane perpendicular to the TM mode magnetic field direction. In this way, for all the TM modes under investigation the magnetic field **H** perpendicularly excites each ring (parallel polarization) enhancing the SRR resonances and minimizing the power transferred to the cavity at the same time [6].

III. Experimental results

The response of the cylindrical pillbox cavity is measured using a 2-port Vectorial Network Analyser (VNA) Rohde & Schwarz ZNB 20 in the frequency range between 1.0 GHz and 5 GHz. In this spectral window, five TM modes are excited using two axial antennas.

SRR-based absorbers are placed on a rigid support made of a low loss, low dielectric constant material, with their plane perpendicularly oriented with regard to the magnetic field and facing the lateral cavity wall at a distance of 10 mm. As a consequence of this geometrical configuration, the magnetic resonance excited in the SRR arrays exceeds by far the resonance induced by the electric field travelling parallel to the pillbox longitudinal axis [7].

Fig. 2(a) shows the experimental transmission scattering parameter inserting sample (b), compared with the spectrum of the empty pillbox cavity. This absorber shows its intrinsic resonance in close proximity with the frequency (@ 2.14 GHz) of the TM_{011} transverse-magnetic mode excited in the pillbox cavity. Therefore, since the absorption frequency bandwidth of the SRR array overlaps a resonance of the empty cavity, a "disruption" effect is visible in the spectrum (and highlighted in the squared box). A clear decrease in the overall transmission response of the cavity at the designed frequency (-47 dB @2.1 GHz) is clearly seen (Fig. 2(b)), as expected from electromagnetic simulations. Conversely, outside the highlighted frequency window, the only effect being produced is a rigid shift in the pillbox resonances towards lower frequencies, larger than one can observe from the insertion of the dielectric substrates only. In this case, therefore, the presence of the array has also only a minor effect on the TM modes of the cavity.

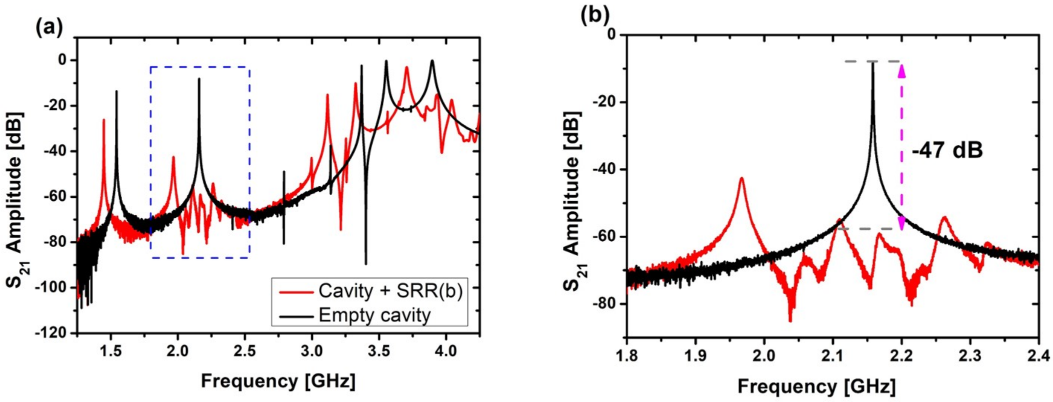

Fig. 2. (a) Transmission parameter of the empty pillbox cavity (black curve), compared with the cavity loaded with the SRR-based metamaterial sample (b) (red curve). (b) Details of the second cavity mode TM_{011}, highlighted in the squared box in (a), where a "disruption" effect is observed (-47 dB @ 2.1 GHz).

III. Conclusions

The aim of this work is to study how 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 may help into mitigating beam instabilities related to collective effects in particle accelerators.

Simulations and measurements performed on SRR-based structures inside a simple pillbox cavity, as a function of ring dimensions and of the dielectric substrate, show their potential use as single mode dampers in a wide range of frequencies. The analysis of field distribution inside the cavity confirms that SRRs reduce the field intensity in the specific frequency range without introducing new modes. Further studies call to obtain wide band absorbers based on hyperbolic metamaterial-based absorbers. This might open the way to the introduction of a new typology of HOM dampers inside real components in circular or linear accelerators.

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