APPROACHING TO A MONO-MODAL ACCELERATING CAVITY BASED ON PHOTONIC BAND-GAP CONCEPTS

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Abstract

One of the main problem of high intensity accelerators is the presence of higher order modes (HOMs) which might degrade the beam quality. Accelerating cavities require HOMs suppression whereas keeping a high quality factor (Q) for the fundamental mode. Both these requirements can be hardly met in closed metallic cavities. At low frequency and for particular geometries it is possible to partially suppress HOMs. At high frequency and for superconducting cavities these configurations become cumbersome and technically unviable. We propose here a high Q cavity based on Photonic Band Gap (PBG) concepts, operating in the microwave region [1,2]. This cavity is intrinsically quasi-monomodal: HOMs can be efficiently suppressed without affecting the fundamental mode. We will present the study, the optimisation and the measurements of our metallic (Copper) PBG structure working in the 0.5-20 GHz range. Studies on different configurations working in the same frequency band are also discussed for room and low temperature measurements. The prototype of a hybrid metallic-dielectric PBG cavity will be presented too.

INTRODUCTION

A PBG system [3,4] is based on a periodic alignment of macroscopic objects, like metallic or dielectric cylinders. Compared to a traditional cavity, the structure exhibits frequency band-gaps (know as stop-bands) which prevent the propagation of e.m. radiation along the periodicity directions in the structure itself: no structure modes can exists in these gaps. In such a system a cavity can be realized by removing one or more cylinders. In fact, when the lattice contains such "defects", new modes can exist in the frequency stop-bands; they will be localized in the "cavity", decaying exponentially in all directions away from the defect site. In this way, one can obtain a cavity with a very high quality factor, Q, at the fundamental mode. By choosing the appropriate lattice geometry HOMs will fall into the frequency pass bands, exhibiting very low Q's. They will propagate along the structure and could be easily damped using an absorber. By means of proper electromagnetic codes the design of the structure can be optimised according to the frequency requirements. The working mode (localized in the stop-band) can be chosen to be a quasi-TM01 mode, where the electric field is parallel to the beam direction in the centre of the cavity (parallel to the cylinders). By adequately shaping the geometry around the defect, this mode can be optimised as the accelerating mode.

By employing superconducting materials, in principle the fundamental mode Q can be enhanced to much higher values. An alternative configuration consisting of dielectric cylinders plus superconducting plates ("hybrid" configuration) can be used as well. In this paper we present our preliminary work on different structures (copper, dielectric + superconductor, superconducting cavity). Some examples of coupling systems are also shown.

15 GHZ COPPER PROTOTYPE

The cavity consists of a two-dimensional hexagonal lattice, composed of thirty-six metallic cylinders (height 4.6 mm, diameter 3.0 mm, lattice constant 8.6 mm), sandwiched between two Copper plates. In the first prototype we have realised, the Copper rods are not brazed to the structure. The cylinder in the centre of the structure is missing (symmetry break). In this position a hole is created on both conducting plates allowing for the beam clearance; the hole is also used for coupling the cavity to the pick-ups for the experimental characterization. The working frequency of this structure is 14.5 GHz. Fig 1 shows a schematic view of the realized cavity [5].

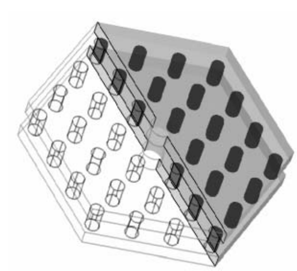

Figure 1. Schematic view of the Copper PBG cavity.

The eigenmodes and the eigenfrequencies of several PBG configurations have been studied using MWS code (3D e.m code of CST™). In Fig. 2, the fundamental mode E-field is shown; the mode is clearly confined inside the first circle of cylinders.

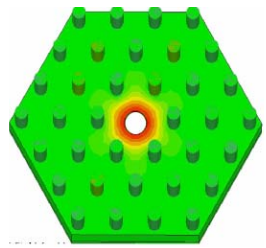

Figure 2. Copper PBG cavity: the color code indicates the different magnitude of the electrical longitudinal field excited for the fundamental mode (14.5 GHz).

The experimental characterization has been carried out using a Network Analyzer through the measurement of the Scattering matrix at room and low (77 K) temperature. Simulations have been performed modelling the structure in the same range of frequencies (10-20 GHz). In Fig. 3 the transmission parameter S_{21} is shown.

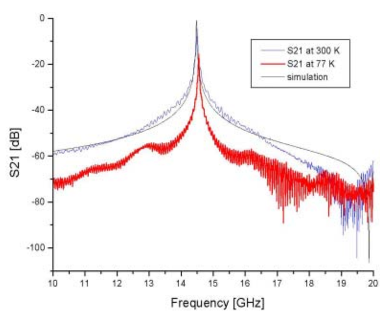

Figure 3. Comparison between experimental (low and room temperature) and simulated S_{21} scattering parameter.

The agreement is very good: the frequency difference between the simulated and measured fundamental mode is less than 1%, implying that this mode is localized and not affected by boundary conditions. A higher mode appears around 20 GHz, which is propagating and depends on the boundary conditions, as it is shown by the disagreement between simulation and measurement. However, it displays a very low Q value, hardly to be measured.

The cavity is therefore quasi mono-modal in the frequency region of interest, showing a quality factor Q = 1900 at 77 K. This value is lower than half of the value predicted by simulations. This difference can be attributed to the additional surface losses in the experimental structure coming from less than perfect electrical contacts between the metallic rods and the upper and lower plates. It is believed that a higher Q would be obtained in a brazed structure.

In order to improve the quality factor without increasing the complexity of the fabricated structure, a new machining technique has been set up to build a PBG cavity starting from an OFHC Copper single piece [6].

The working frequency for the fundamental mode of this second prototype is slightly larger, at 16.4 GHz. We performed room and low temperature (77 K) measurements to yield the Q value in the limit of conduction losses ($Q = G/R_s$) and to compare the experimental geometrical factor (G) with the value estimated by e.m. simulations. R_s is the surface resistance in the local limit, evaluated assuming a Copper conductivity $\sigma = 5\cdot 10^7\ (\Omega\cdot m)^{-1}$.

At room temperature the experimentally measured unloaded quality factor (4100) well corresponds to the value estimated using MWS calculation (4200), yielding a G factor of 135 Ω at 16.4 GHz. We have also measured the unloaded quality factor Q = 8800 @77 K, in full agreement with the expectations for Copper in the normal skin effect region [7].

The cavity shunt impedance was measured by means of a perturbative method based on the Slater perturbation theorem [8], yielding a value of 71 MΩ/m at room temperature and for Q = 4100. This value is higher than for a standard pill box cavity having all HOMs excited, and it could be furtherly increased by shaping the beam hole.

A HYBRID CONFIGURATION

In particle accelerators, full superconducting structures are limited by the difficulty of achieving high quality, low loss, surfaces across large size. An alternative configuration could be a "hybrid" (dielectric cylinders + superconducting plates) PBG based cavity which could lower metallic losses in the structure. At the same time, superconducting materials in a flat geometry is only required, which might reduce possible field emission on its surface. By using low loss dielectrics, such a mono-modal cavity might be suitable for high gradient field applications.

A hybrid cavity (sapphire cylinders + Copper (or Nb) plates) has been designed and constructed at 15 GHz to be tested at low temperature (at 77 K, and in the future at 4 K). In Fig. 4 a picture of this structure with Copper plates is shown.

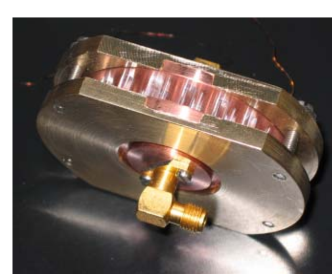

Figure 4. The hybrid metallic-dielectric PBG cavity: sapphire cylinders between two Copper plates. One of the connectors and the external clamping system are also shown.

First tests at room temperature show the mono-modal behaviour even if the field is not so well confined as in the all-metallic case (the ratio between Emax in the centre and Emax on the 3rd rod circle is roughly 0.5). Simulations show that adding a 4th circle of metallic cylinders the E field can be lowered by a factor 10. In Fig. 5 the calculated E-field amplitude is displayed for the two structures. The minimum corresponds to the cylinder positions. A field reduction is evident after the 3rd circle. This behaviour indicates that the radiation pattern of the hybrid structure can be improved by adding circles of metallic cylinders, in order to reach the field confinement of the all-metallic structure simultaneously maintaining the high field gradient of the hybrid cavity.

The S_{21} parameter measurement at room temperature is reported in Fig. 6 and compared with the simulation. Also in this case, the frequency agreement is very good, roughly 0.1%. However, the Q value is lower than expected (about 1000), due to radiative and coupling problems, which need further studies. The value estimated by MWS simulation is 10^4 , larger than in the all-metallic symmetrical structure since surface metallic losses have been lowered.

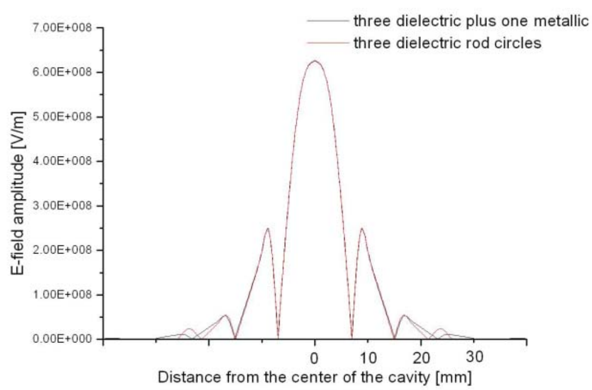

Figure 5. E-field amplitude along a line in the cavity centre. Comparison between 3 dielectric circles and the case adding a 4th metallic circle.

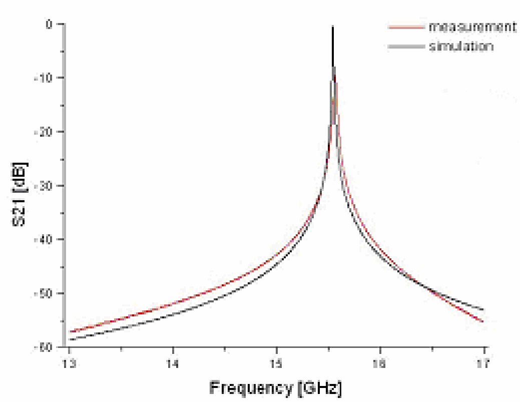

Figure 6. Hybrid cavity S_{21} parameter: comparison between experimental data (at room temperature) and simulation.

FUTURE WORK AND CONCLUSIONS

Studies on coupled cavities are in progress to improve the feeding system too. In Fig. 7 a possible configuration is shown with two accelerating cavities and an aside coupling cavity for the RF feeding system.

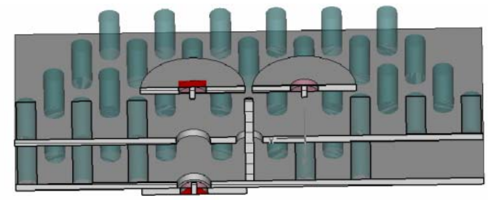

Figure 7. A schematic design showing a possible way to realize a coupled PBG cavity (MWS figure).

In this paper simulations and measurements on some PBG based cavities at room and liquid nitrogen temperature have been presented, in order to study their RF behaviour. All-metallic (Copper) and hybrid (Sapphire + Copper) cavities show the mono-modal behaviour, as expected. There is a substantial agreement between the estimated and measured quality factors for the all-metallic prototypes. Radiation seems to be a major problem for the hybrid structure, even if the Q value seems to be presently limited by the external coupling circuit. Preliminary studies on possible coupling systems between cavities to produce a multicavity accelerating cell have been shortly presented as well.

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