PBG SUPERCONDUCTING RESONANT STRUCTURES

M. R. Masullo, INFN-Napoli, Napoli, ITALY
M. Panniello, V. G. Vaccaro, Università di Napoli “Federico II” and INFN, Napoli, ITALY
A. Andreone, E. Di Gennaro, F. Francomacaro, G. Lamura,
Università di Napoli “Federico II”, Napoli, ITALY
V. Palmieri, D. Tonini INFN/LNL, Legnaro, Padova, ITALY

Abstract

We have realized normal conducting and superconducting “open resonators” based on the Photonic Band Gap (PBG) concept. We present the study, the optimisation and the measurements (from room temperature to 1.5 K) of Copper and Niobium PBG accelerating cavities operating at two different frequencies, 6 GHz and 16 GHz. All the structures are realised by extruding a single bulk piece of material, using a new machining method that minimizes the surface losses caused by the contact between different conducting parts. Measurements on the compact (54 mm external diameter) 16 GHz Nb structure are very good, showing in the superconducting state a quality factor Q $=1.2\text{x}10^5$ at the lowest temperature (1.5 K), limited by radiation losses only. The shunt impedance measured for the 16 GHz prototype is 70 MΩ/m, underlining the applicability of such resonant structures as accelerating cavities.

INTRODUCTION

The presence of higher order modes (HOMs) is one of the main limitations in the performance of high intensity RF accelerators, since HOMs degrade the beam quality. The standard solution in accelerating cavities is the use of dampers designed to suppress higher order modes keeping simultaneously a high quality factor for the fundamental mode. At high frequencies, however, the design of closed resonant structures having dampers able to satisfy both these requirements become cumbersome and technically unviable. A cavity based on the PBG concept is designed without the need of external couplers. In this novel configuration, HOMs are *intrinsically* suppressed without affecting the fundamental mode. A PBG system, in fact, is based on the periodic alignment of macroscopic objects, like metallic or dielectric cylinders. This open structure exhibits frequency band-gaps preventing the propagation of e.m. radiation along the periodicity directions in the structure itself [1-3]. Using this principle, one can create “defect” modes where e.m transmission is allowed by removing one or more rods. In fact, when the lattice contains such “defects”, new modes can exist in the frequency stop-bands, localized in the “cavity” and exponentially decaying in all directions away from the defect site. In this way, one can get a cavity with e.m. fields well confined at selected modes, exhibiting therefore a very high Q. Furthermore, by using superconducting materials, the quality factor of the localised mode can be enhanced to extremely high values. HOMs will fall into the frequency pass bands and, in a infinite lattice, are modes propagating throughout the structure.

EXPERIMENTAL SETUP

In designing a real cavity one has to face the finite dimensions of the structure, that obviously affects the ideal response of an infinite lattice. Typical effects are the lowering of the quality factor for the localised mode, due to radiation losses, and the presence of other modes in the pass-band frequency region. However, by optimising the lattice geometry, or removing some cylinders, Q’s of spurious modes can be reduced to very low values. Moreover, as we learned from the characterization of a previous cavity described in [4], the mechanical assembly, which affects the electrical contact between the different conducting parts, is a very crucial issue. Actually, a poor electrical contact can sensibly lower the overall Q of the cavity. Another issue to take into account is the low mechanical tolerance needed for the best performance, that can limit the applicability of PBG structures in a LINAC, where a large number of cavities are required.

In order to overcome all these problems without increasing the complexity of the fabricated structure, we propose a new machining technique to build a PBG cavity starting from a single piece of metal [5].

With this technique we have realised two different cavity prototypes starting from the same design and suitably scaling it to obtain working frequencies of 6 GHz and 16 GHz. At both frequencies a Copper and a Niobium cavity have been built. Figure 1 shows the 6 GHz Copper prototype, with the chosen two-dimensional hexagonal lattice. The prototype at 6 GHz exhibits holes inside the columns to let liquid helium in and therefore improve the cooling performance, very crucial for the cavity made of Niobium.

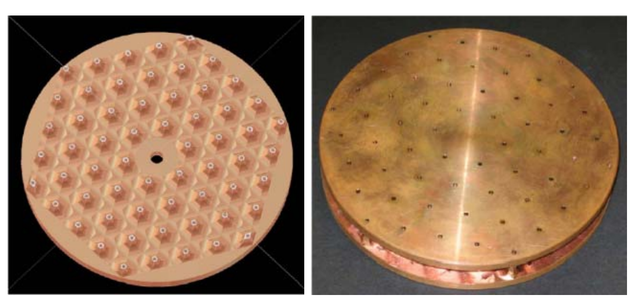

Figure 1: The 6 GHz PBG cavity prototype: a) cross section layout; b) top view, showing the holes for the cooling.

The higher frequency prototype was conceived with the idea of performing measurements at low temperatures, that, due to its compactness, are easier to be done in standard cryostat. Both structures have been realised in Copper and in Niobium in order to test the machining, the pick-up configuration and the cooling system at 6 GHz.

16GHz Prototypes

The 16GHz prototype consists of three rows of columns composed of 36 elements (height 5 mm, lattice constant 7.5 mm), between two external Copper (or Niobium) plates (total diameter 54 mm). The structure differs from the one shown in figure 1 for the lower number of rows (3 instead of 4), due to the cryostat dimensions, for the central beam hole present on both plates.

The positions of the feeding coupler and of the pick-up have been optimised for this prototype at room and at low temperatures (Niobium) in order to be applied to the case at 6 GHz.

Figure 2 shows some available pick-up configurations used for the measurements. The setup (a), with the coupler on the beam port and a lateral pick-up, is the best one for the Niobium prototype at low temperatures. It has been chosen also for the final measurements on the 6 GHz cavity.

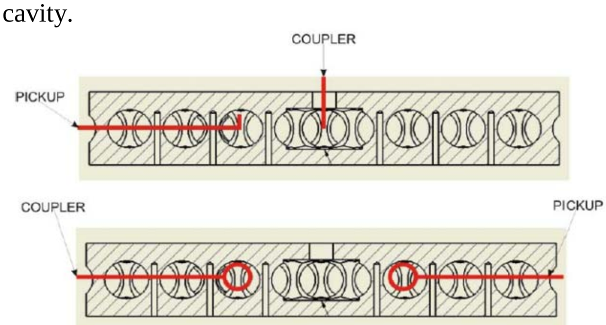

Figure 2: The a) electric and b) magnetic feeding coupling configurations.

The working frequency for the fundamental mode of this new prototype is roughly 16.4 GHz.

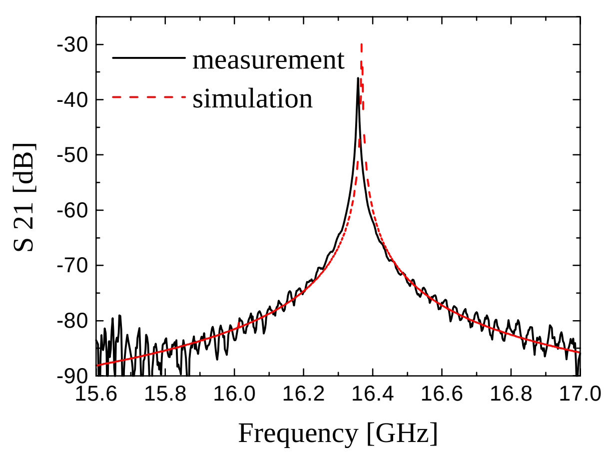

Figure 3: The measured and simulated transmission parameter at room temperature for the 16.4 GHz Copper cavity.

As shown in figure 3 the Microwave Studio (MWS) cavity simulation in the fundamental mode frequency region gives an excellent result when compared with the measured transmission scattering parameter at room temperature. The two peaks of the S21 parameter differ for less than 0.07 %. At room temperature the experimentally measured unloaded quality factor (Q_{un} = 4200).

Using a suitable cryogenic apparatus we performed transmission measurements in the frequency domain from room temperature until 77 K to yield the Q value in the limit of conduction losses ($Q = \Gamma/R_s$ where Γ is the geometrical factor and R_s is the surface resistance) and to compare the experimental results with the value estimated by e.m. simulations. R_s is evaluated in the local limit assuming a Copper conductivity $\sigma = 5.9\cdot10^7$ $(\Omega\cdot m)^{-1}$. The Q measurement at room temperature yields a Γ factor of 140 Ω, assuming that only ohmic losses are relevant.

In figure 4 the Q_{un} temperature dependence is shown, in full agreement with the expectations for Copper in the normal skin effect region [6], where $Q^{-1} \propto \sqrt{\rho_0 (1+\alpha\Delta T)}$.

From the numerical fit it is also possible to extract the resistivity thermal coefficient α = 3.98 10^{-3} K^{-1} that coincides within the experimental error with the literature data [7]. Note (Fig. 4) that these features were not found in the previous cavity configuration [4], where the quality factor was lower and only slightly temperature dependent, due the poor electrical contact among the plates and the rods.

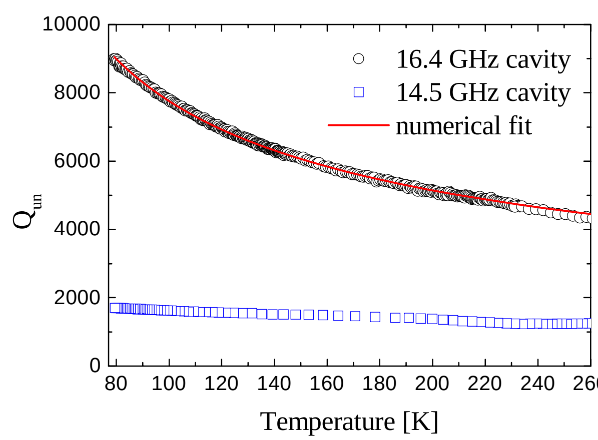

Figure 4: The unloaded quality factor for the 14.5 GHz and 16.4 GHz Copper cavity configurations.

The cavity shunt impedance was measured by means of a perturbative method based on the Slater perturbation theorem [8], yielding for Q = 4200 a value of 70 MΩ/m at room temperature. This value is higher than for a standard pill box cavity which has all HOMs excited, and it could be increased even further by shaping the beam hole.

The same structure has been built in Niobium and tested from room temperature to 1.5 K. Measurements gave an operation frequency of 16.1 GHz, with a slightly difference respect to the Copper case. Likely this can be due to small differences in the realization of these first prototypes: different expedients used in the extruding material process and a not optimized technique for the removal material in the defect zone.

Figure 5 shows the unloaded Q behaviour as function of the temperature. A value of $1.2x10^5$ is reached at 1.5 K. Assuming that the geometrical factor is the same for both Copper and Niobium cavities, we can deduce, from these Q data, a R_s value of 1.4 mΩ @ 4.2 K, a factor ten above the expected literature value [6] scaled with the well known ω^2 law.

The machining technique from a single piece of bulk material and the surface polishing treatment ensure that no conducting losses, due to poor electrical contact or local surface defects, are present.

Only assuming that radiation losses have to be included as dissipation mechanism, we can justify the previous disagreement for the superconducting structure. In the Copper cavity case, this term is not relevant respect to conducting losses in the total quality factor computation. Only three column rows are not sufficient to guarantee the complete field confinement.

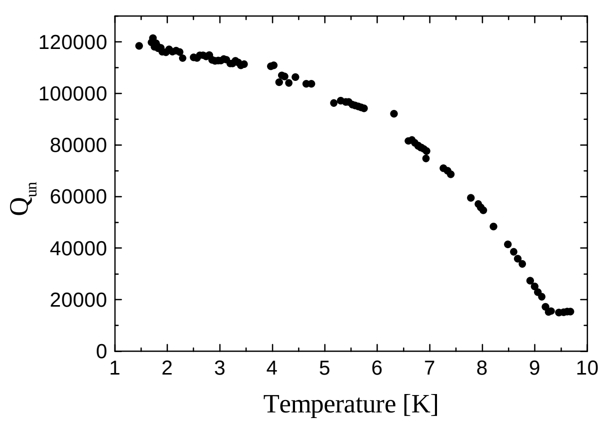

Figure 5: The unloaded quality factor for the 16.1 GHz Niobium cavity.

6GHz Prototypes

In order to improve the field confinement, the 6 GHz prototypes have been realised with 4 column rods. The cavity is composed of 60 elements (height 6 mm, lattice constant 16.4 mm), the external Copper (or Niobium) plates have a diameter of 160 mm.

Due to the dimensions of the cavity and to the large amount of material to be cooled , an ad-hoc cryostat has been designed and realized at the National Laboratory of INFN in Legnaro for the cryogenic measurements on the Niobium cavity.

Q measurements will be performed in the time domain, because we expect values higher than 10^6. First measurements will be realised on the Copper prototype at room temperature to optimize the pick-up coupling system. Measurements on both cavities are under way.

CONCLUSIONS

From our previous studies on PBG Copper cavities made of rods inserted between two conducting plates, further prototypes based on a new machining technique have been realized.

In the case of the normal conducting cavity operating at 16 GHz, the unloaded quality factor temperature dependence from 300 to 77 K follows the normal skin effect regime predicted for Copper, confirming that in the new configuration Q is entirely due to ohmic losses in the bulk material. The superconducting prototype operating at the same frequency has been measured at cryogenic temperatures, reaching a maximum Q value of $1.2x10^5$ at 1.5 K. In this case radiation losses dominate the electrodynamic response of the Niobium cavity. To overcome these limitations in the performance, an additional row of cylinders has been added in the prototypes operating at 6 GHz. Measurements on these cavities both at room and cryogenic temperatures are under way.

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