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A NOVEL PULSE COMPRESSOR WITH DIELECTRIC ASSISTANCE

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Abstract

A compact pulse compressor with dielectric assistance structure is proposed and simulated. The novel pulse compressor adopts a spherical resonant cavity design with dual-mode polarization mode. A dielectric sphere added at the centre of the spherical cavity can reduce the volume and weight of the pulse compressor and improve the unloaded quality factor of the cavity. A C-band compact storage cavity model is designed and simulated on ANSYS HFSS working on 5.712 GHz. The dielectric permittivity of the dielectric sphere is 9, and the dielectric tangent loss is 0.00001. The simulation of the dielectric-assist resonant cavity with an inner diameter of 34 mm indicates an unloaded quality factor about 72000.

INTRODUCTION

With a history of over forty years, high power microwave pulse compression is an important branch of the field of accelerators and high-power microwave (HPM). The microwave device that implements pulse compression is called pulse compressor. Pulse compressors can compress long microwave pulses with relatively low power into short microwave pulses with high power. The peak power of output pulses will increase several to tens of times.

In 1973, SLAC (Stanford Linear Accelerator Center) began the development of pulse compressors, which can double the energy of electrons based on the original accelerator equipment, called SLED (SLAC Energy Doubler) [1]. SLED is a passive technique and has become indispensable in the recent accelerator systems. In the 1980s and 1990s, within the process of collider project from Russia, a new design of pulse compressor named BOC (Barrel shaped Open Cavity) pulse compressor was advanced by Igor et al. BOC pulse compressor only requires one complex resonant cavity to achieve the functions of pulse compression, while SLED requires two identical resonant cavities. In 1990, the SLED advanced to a new one called SLED-II, which replaced the two cavities with two identical delay lines, to generate rectangle output pulse instead of the exponentially decaying pulse.

In 2014, Juwen Wang and others from SLAC proposed a super-compact SLED system which adopted a sphere cavity with the working mode of TE114 [2]. The TE11n mode of the sphere cavity has two degeneracy modes with identical frequency, and therefore the new sphere cavity can substitute for the two cavities in the original SLED system. In 2018, an S-band compact pulse compressor was designed and fabricated with a single spherical resonant cavity and an RF polarizer for the S-band high power test facility at Tsinghua University [3]. It reached the average power gain of 5.2 with a compression ratio of 12. In 2022, a compact X-band two-stage RF pulse compression system was designed and tested at Tsinghua X-band high-power teat stand [4]. The system consists of a correction cavity chain, a first-stage, and a second-stage storage cavity. It achieved a peak power of 320 MW with a gain factor of 9.7.

In order to achieve a high peak power gain, the cavity in the pulse compressor requires a high quality factor. We need to increase the volume of the cavity to obtain the higher quality factor. For example, the Q of the sphere cavity only depends on the sphere radius without depending on the mode types. The unloaded quality factor Q_0 for TE mode in the sphere cavity is

$$Q_0 = \frac{a}{\delta}$$

Where a is the radius of the sphere; δ is the skin depth.

However, the enlargement of the cavity will lead to an increase in volume and weight. It becomes inconvenient to transport and mount such a large cavity. The larger cavity also means the higher mode of electromagnetic field, which results in the unwanted mode in the cavity. So, we need a balance between the volume and the Q of the cavity in the pulse compressor.

In this thesis, we proposed a novel design of pulse compressor with dielectric assistance. The dielectric assistance can decrease the volume and weight of the cavity, and increase the Q of the cavity.

STRUCTURE DESIGN

Accordance with the former design of the super-compact pulse compressor by Juwen Wang, the SLED system is composed of a spherical cavity and a dual-mode polarizer as shown in Fig. 1.

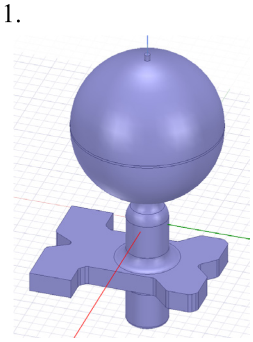

Figure 1: Schematic view of the former super-compact pulse compressor.

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Because the electromagnetic field of the TE11n mode is concentrated in the centre of the spherical cavity. In order to effectively reduce the volume and weight of the spherical cavity, we propose to add a dielectric sphere in the centre of the cavity as shown in Fig. 2. The dielectric can make electromagnetic field more compact so the size of the cavity will decrease. The reduction radio depends on the permittivity of the dielectric material. The higher permittivity dielectric material leads to the smaller cavity.

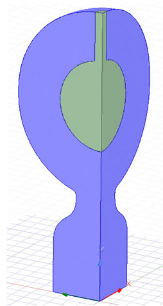

Figure 2: Schematic view of the 1/4 model of the cavity with dielectric assistance. The green part in the centre is the dielectric and the blue part is vacuum.

Besides the permittivity of the dielectric, the low dielectric loss is also required to achieve a substantially higher quality factor. The sapphire may be the suitable dielectric material for this structure. The permittivity of the sapphire is about 10 and the dielectric tangent loss is around 10^{-5}. In the following calculation and simulation, the permittivity of dielectric material is 9, and the dielectric tangent loss is 1×10^{-5}.

Because the electric field of the TE11n mode in the spherical cavity is parallel to the spherical surface. The radio of the dielectric sphere and vacuum sphere's radius should be specified values to satisfy the boundary conditions of the electromagnetic field. In this paper, the sphere cavity works in the TE112 mode at 5.712 GHz. The radius of dielectric sphere is 0.5 time of the cavity's radius.

The spherical cavity with dielectric assistance is simulated by HFSS. The structure dimensions of cavity with and without dielectric is presented in Table 1.

Table 1: Cavity Structural Parameters

Parameters	Without dielectric	With dielectric
Frequency	5.712 GHz	5.712 GHz
Mode	TE112	TE112
Radius of cavity	64 mm	33.8 mm
Radius of dielectric sphere	-	16.9 mm

As shown in Fig. 2, the dielectric sphere is fixed at the centre of the cavity by a rod. The rod is composed of the identical dielectric material to reduce the effect to the electromagnetic field. The radius of the rod is 3 mm in this model.

SIMULATION

The cavity model with dielectric assistance is simulated by the HFSS. The prime parameter we considered is the unloaded quality factor (Q_0) of the cavity. The quality factor (Q) of the cavity can be acquired through the S11 curve of the simulation results. The S11 curve of the dielectric assisted cavity is shown in Fig. 3.

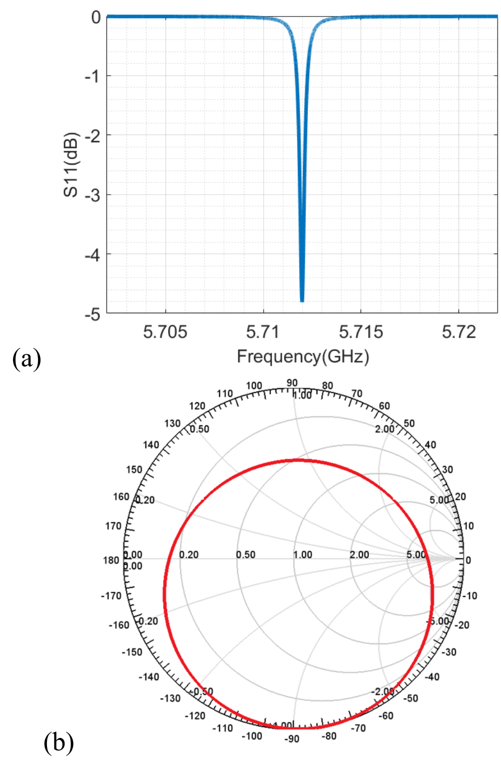

Figure 3: S11 parameter of the spherical cavity with dielectric assistance including frequency spectrum (a) and smith chart (b).

For comparison, the model without dielectric and without dielectric loss are also simulated at the same boundary condition. The unloaded quality factors for three cases are listed in Table 2.

It is shown that the Q_0 of the cavity with dielectric but without loss is about 3 times that of the cavity without dielectric. Although the Q_0 of the cavity with dielectric and loss is about equal to the cavity' Q_0 without dielectric, the radius of the cavity with dielectric is almost 0.5 time that of the cavity without dielectric shown in Table 1. It is proved that the novel sphere cavity with dielectric assistance achieves the purpose of compact cavity while maintaining the quality factor without decreasing.

Table 2: Simulated Q_0 of Three Cavities

Cavity	Q_0
Without dielectric	70000
With dielectric but without loss	194000
With dielectric and with loss	72000

Another significant parameter is the electromagnetic field intensity. The magnetic field on the surface of the

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metal determines the heat generation. The dielectric strength of breakdown limits the maximum of the electric field in the cavity. The electric and magnetic field distribution inner the cavity is presented in Fig. 4. The magnitude of the input power is 1 W. It is shown that the electric and magnetic fields are concentrated in the dielectric sphere with compact size. The electric field distribution along the radius of the spherical cavity without and with dielectric is presented in Fig. 5.

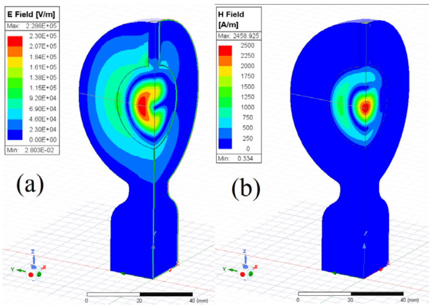

Figure 4: Electric field (a) and magnetic field (b) of the sphere cavity with dielectric assistance working in TE112 mode with an input power of 1 W.

Similarly, the electric and magnetic field strength of three cases mentioned above are also obtained by simulation, and these parameters are listed in Table 3 for comparison. The maximum field intensity appears at the centre of the spherical cavity, while in the dielectric sphere as shown in Fig. 4. The maximum surface magnetic field intensity is situated on the coupler iris.

Table 3: Electromagnetic Field of Three Cavities

Parameters	**Without dielectric**	**With dielectric but without loss**	**With dielectric and with loss**
Maximum electric field strength [V/m]	1.33×10^5	4.05×10^5	2.29×10^5
Maximum magnetic field strength [A/m]	485.0	4372.9	2458.9
Maximum surface magnetic field strength [A/m]	148.9	261.8	159.8

By comparison, it can be concluded that the electric and magnetic field intensity in the dielectric cavity is several times that in the original vacuum cavity. For example, the maximum electric field intensity in the dielectric cavity is about two times that of the vacuum cavity. However, the surface magnetic field of the new cavity is almost equal to that of the cavity without dielectric. This will result in a less significant increase in heat generation.

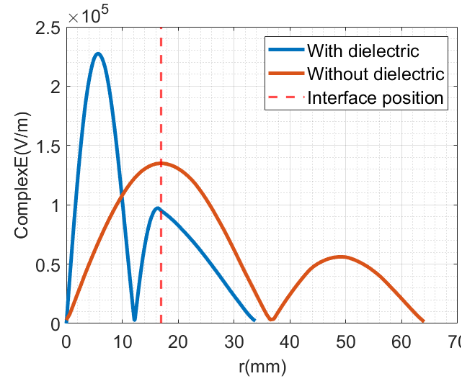

Figure 5: Electric field distribution along the radius of the spherical cavity without and with dielectric.

CONCLUSION

In this paper, we propose a novel cavity design with dielectric assistance for pulse compressor. A dielectric sphere is added at the centre of the dual-mode spherical cavity, fixed by a dielectric rod. The new spherical cavity has the advantage of the compact structure to reduce the volume and weight of the cavity.

Through simulation by HFSS, it is obtained that the radius of the dielectric cavity is about 0.5 times that of the cavity without dielectric, while maintaining the unloaded quality factor constant. The radius of the dielectric cavity is 33.8 mm and the unloaded quality factor is 72000.

In the future work, it is planned to consider the dielectric strength about electric breakdown of the material. The electric breakdown in the cavity will destroy the vacuum and affect the microwave pulse. The suitable dielectric material is required to achieve the high dielectric strength, high permittivity and low dielectric tangent loss. A suitable material includes sapphire, ceramics or other engineered dielectric materials.

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