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PIC Simulation of a Double Side-cavity Reltron, Calculation of Cavity Reactance and Comparison with Conventional Reltron

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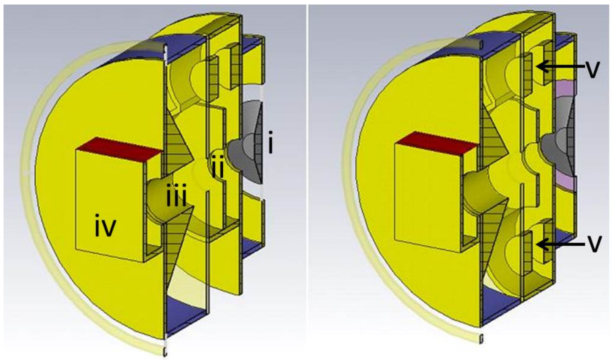
Abstract

A double side-cavity reltron is proposed and simulated using CST particle studio which predicts ∼20 % increase in the pulse duration than a conventional reltron. A comparison of the beam wave interaction study and the cavity reactance in the first three normal modes (0, $\pi/2$ and π) among the conventional reltron and the double side-cavity reltron is also presented. The inductance and capacitance are calculated from loaded quality factor (Q_l), by assuming the tank circuit equivalent model of a cavity resonator. The frequency domain solver of CST microwave studio is used to find the Q_l of the cavity from normalized S_{11}.

1 Introduction

Reltron [1] is a new class of high power microwave (HPM) oscillator that uses the post-acceleration technique for producing a power of 100 MW to 1 GW with ∼40% efficiency. It can provide – a tunable range of 15% [2], pulse repetition frequency (PRF) of up to 100 Hz [3], pulse duration up to 1 μS and a good frequency stability during the entire pulse. It can cover an extensive frequency range of 0.7 to 11 GHz [3] by using replaceable modulation and extraction cavities for extracting the fundamental mode and higher order harmonics. Combination of pulse duration and PRF widens the variety of electronic equipment defenceless against reltron based direct energy weapons. However, there are a few shortcomings of reltron like - pulse shortening due to the enhanced electric field inside the cavity, pulse-repetition-rate limitation by vacuum requirement of less than 10^{-4} torr, secondary emission and plasma formation [4].
A double side-cavity reltron is proposed here that enhances the pulse duration and a comparison of beam wave interaction study among the conventional reltron and the proposed double-side cavity reltron is carried out. Simulation results show that the oscillation builds up quickly in double-side cavity reltron and thus, the effective pulse duration is more than that of a conventional reltron. The inductance and capacitance of the modulation cavity of both kinds are also calculated for the first three normal modes. The PIC simulation results also show that the second harmonics contain a significant amount of power, that can be extracted by a separate extraction cavity and radiated through a secondary radiator in both the kinds of reltron.



(a) (b)

Figure 1. Model of – (a) conventional reltron with i) cathode, ii) modulation cavity, iii) post acceleration section, iv) extraction cavity and (b) double side-cavity reltron with two v) side cavities.

2 Construction

A reltron consists of four main parts – cathode, modulation cavity, post-acceleration section, and extraction cavities as shown in Figure 1 (a).

2.1 Beam Injector

Velvet cathodes [5] are used in high peak power grided reltron because – it has low threshold electric field of ∼16 kV/cm, less plasma velocity of 0.25 cm/μS, high emission density of 1 kA/cm^2, and constant impedance for a considerably long period of 1 μS duration. It is constructed by attaching a circular piece of velvet cloth to an aluminium base-plate by means of a corona ring to prevent breakdown at edges. Velvet is a composite of 75% rayon and 25% silk and the tuft density varies from 80 - 250 /cm. The vacuum level of less than 10^{-4} torr must be maintained for the velvet cathode to operate without arcing. It requires tens of shorts to condition the tube after a breakdown has occurred. However, the erosion rate of 5 x 10^{17} atoms/pulse limits the cathode lifetime to 10^5 pulses and the PRF to less than 20 Hz for a pumping speed of 500 l/S [4].

2.2 Modulation Cavity

Reltron modulation cavity is a three cavity structure with three normal modes – 0, $\pi/2$ and π [1]. A cylindrical main cavity is divided into two – the first and the second cavity, by three grids. A third re-entrant cavity is side coupled to the main cavity and it provides magnetic coupling among the first two. The grids are made of wire mesh made of stainless steel (SS), molybdenum, or tungsten. 1 mil tungsten wires woven to form a rectangular grid with 40 wires per inch produces higher beam modulation and faster tube conditioning. Gridless reltron uses a metal disc with a hole at the centre for the passage of the beam. It is experimentally found that the pulse duration is inversely proportional to frequency and the peak power is inversely proportional to the square of frequency [4]. For beam bunching, reltron utilizes the $\pi/2$ mode like a split cavity oscillator (SCO) [6].

2.3 Postacceleration Section

A high positive potential is applied at the exit of the modulation cavity to accelerate all the electrons of the beam. It reduces the kinetic energy spread among the fastest and the slowest electron in the bunched beam by boosting all the electrons to relativistic velocity. Reduction in kinetic spread results in high output power as well as efficiency.
The peak efficiency without post-acceleration is about 20% which doubles with post-acceleration and peak power increases 15-fold [1].

2.4 Extraction Cavity

The post-accelerated beam passes through a rectangular output cavity across its smaller dimension such that the beam excites TE_{10} mode in the cavity eliminating the need of a mode converter. The cavity is designed such that its resonant frequency is matched with the driving beam to maximize the power output. Multiple cavities of the same dimension can be positioned to extract power in the same phase from a particular mode and can be added together for higher radiation intensity. Cavities of smaller dimension can be used to extract power from the harmonics as well.

3 Operation

A high-voltage power supply makes the field emission type velvet cathode emit a space charge limited electron beam. As the beam travels through the modulation cavity, beam field interaction takes place resulting in an intense bunching. This bunched electron beam is accelerated in the post-acceleration section by a high positive potential that makes the beam to achieve the relativistic velocity, without disturbing the spatial bunching. The RF power is extracted through iris loaded low Q extraction cavities in dominant TE_{10} rectangular waveguide mode. Multiple cavities can be used for extracting power from the relativistic beam unless the bunching is lost. The spent beam is collected by a beam dump made of SS or high-density graphite. X-ray shielding is compulsory for reltron. Lead shell of 11 cm thickness is required to provide protection for exposure time less than 50 hours/ year [7].

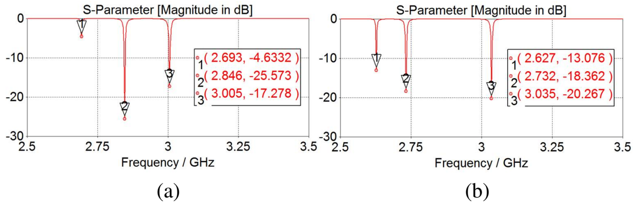


Figure 2. Plot of S_{11} (normalized to 50Ω) of – (a) conventional, (b) double side-cavity reltron.

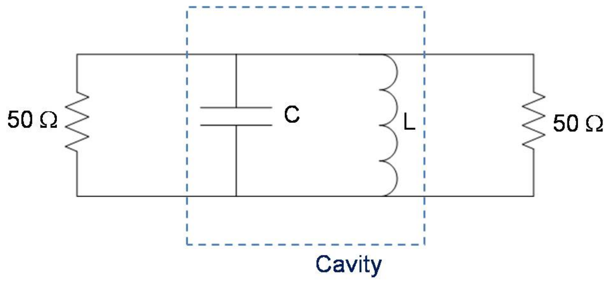


Figure 3. Equivalent model of reltron cavity for obtaining S parameters.

4 Double Side-cavity Reltron

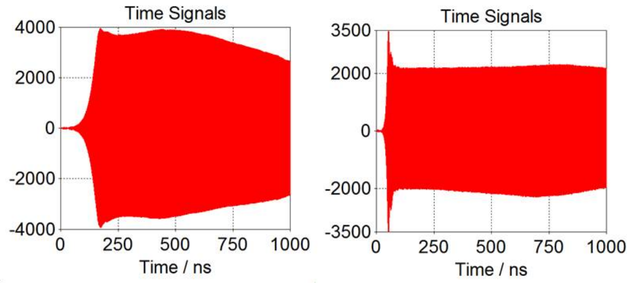
Coupling between the first and the second cavity occurs through the side-cavity only. The coupling can be increased by increasing the coupling depth, but can not be increased indefinitely because of the two limiting factors. Firstly, the dimension of the idler disk limits the insertion of the side cavity into the main cavity. The idler disks play an important role in maintaining the separation among the normal modes and hence restricts the coupling to certain limits. Secondly, the frequency of $\pi/2$ mode goes down with the increase in coupling depth and may reach below the cut-off, ceasing the oscillation. One possible solution of increasing the coupling among the first and the second cavity without disturbing the resonant frequency and separation among them is to include two side cavities coupled to the main cavity opposite to each other with respect to the beam axis as shown in Figure 1 (b).

5 Calculation of Inductance and Capacitance

For obtaining the S-parameters, the standard probe coupled flange mount SMA connectors are modeled in both the side of the modulation cavity along the beam axis. Frequency domain solver is used to obtain S_{11} shown in Figure 2. It shows three distinct minima occurring at the frequencies corresponding to the normal mode frequencies, as predicted by the eigenmode solver. Q_l is calculated from S_{11} using (1)

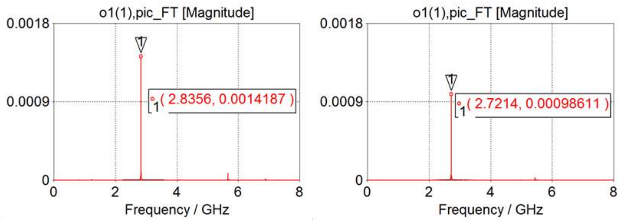
$$Q_l = \frac{f_0}{\Delta f} \tag{1}$$

where f_0 is the resonant frequency and Δf is the -3 dB bandwidth. Here the parallel L-C equivalent model of the



(a) (b)

Figure 4. Temporal field amplitude of – (a) conventional, (b) double side-cavity reltron.



(a) (b)

Figure 5. Frequency spectrum of port signal of – (a) conventional, (b) double side-cavity reltron.

resonant cavity with 50Ω ports at both the ends is considered as shown in Figure 3. For such a circuit, Q_l is given by

$$Q_l = \frac{B}{G} = \frac{1/\omega L}{1/R_{eq}} \quad or \quad \frac{1/\frac{1}{\omega C}}{1/R_{eq}} \tag{2}$$

where G and B are the conductance and susceptance respectively and R_{eq} is the equivalent resistance of the two ports, which is $(50 \parallel 50)\ \Omega = 25\ \Omega$. So, L and C can be calculated using

$$L = \frac{R_{eq}}{\omega Q_l}, \qquad C = \frac{Q_l}{\omega R_{eq}}. \tag{3}$$

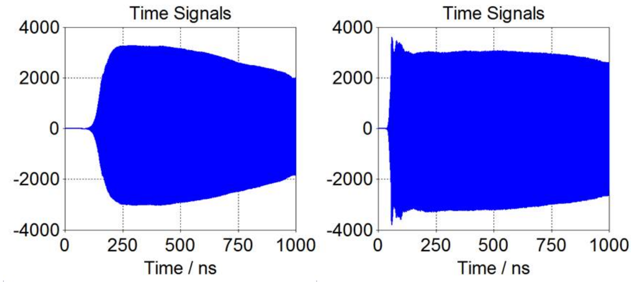
The calculated values of L and C are summarized in Table. 1.

6 Beam Wave Interaction Results

A reltron tube is designed for operating in S-band as per the design principles described in [1]. The cavity is then optimized for equal separation among the three normal modes,

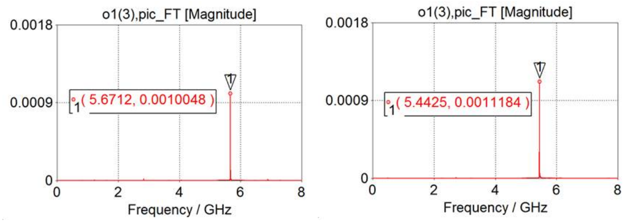
Table 1. Inductance and Capacitance of the Three Modes of Conventional and Double Side-Cavity Reltron

Normal	Conventional reltron				Double side-cavity reltron			
mode	freq. (GHz)	Q_l	L(pH)	C (nF)	freq. (GHz)	Q_l	L(pH)	C(nF)
0	2.693	610	2.42	1.44	2.627	474	3.19	1.15
$\pi/2$	2.846	278	5.02	0.62	2.732	298	4.88	0.69
π	3.005	283	4.66	0.60	3.035	328	3.99	0.688



(a) (b)

Figure 6. Temporal field amplitude of the second harmonics of – (a) conventional, (b) double side-cavity reltron.



(a) (b)

Figure 7. Frequency spectrum of port signal of the second harmonics of – (a) conventional, (b) double side-cavity reltron.

by the parametric study of the cavity. The side-cavity is then mirrored to model a double side-cavity reltron. The structures of both the kinds of reltron are shown in Figure 1 (a), (b).

For the particle in cell (PIC) simulation, explosive emission type SS cathode is used. Discrete ports are used to supply the potential of 100 kV and post-acceleration voltage of 185 kV. A constant magnetic field of 0.35 T is applied along the beam axis. As the beam passes through the modulation cavity, it interacts with various normal modes with different frequencies. Interaction with the $\pi/2$ mode results in a net energy transfer from beam to field resulting in bunching of the beam within a very short axial distance.

The temporal field amplitudes of dominant TE_{10} mode is shown in Figure 4 (a) and (b), which shows the electric field amplitude of the RF signals at extraction cavities of both the reltrons. Fourier transform of the port signal gives the frequency spectrum of the corresponding signals showing frequencies 2.8356 GHz and 2.7214 GHz respectively in Figure 5 (a) and (b). The second harmonics is also excited in the extraction cavity along with the fundamental mode. The temporal fields and their respective Fourier transforms are shown in Figure 6 (a), (b) and Figure 7 (a), (b) respectively.

7 Conclusion

The double side-cavity reltron extends the effective pulse duration by ∼25% but, the output power is reduced to

∼50% of the conventional reltron in the fundamental mode. However, there is no reduction in the amplitude in the case of the second harmonics.

The eigenmode solver predicts there are three resonant modes that satisfy appropriate boundary conditions to exist inside the reltron cavity. The frequency domain solver validates the existence of the three normal modes through the plot of S_{11} which explains, signals with those frequencies suffer very less refection while propagating through the cavity. The Fourier transform of the port signal obtained through PIC solver confirms that only $\pi/2$ mode transfers net energy from beam to the field.

The second harmonics also carries a significant amount of power which may be extracted with separate extraction cavities.

It is important to know the equivalent lumped circuit values of a cavity to introduce beam loading, as the beam can be modeled as a current source with resistive and reactive parts. In fact, the lowered oscillation frequency observed from the frequency spectrum in Figure 5 (a) and (b), than the predicted frequency of $\pi/2$ mode by frequency domain solver in Figure 2 (a) and (b), is the effect of beam loading.

Acknowledgement

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