HEM_{11} mode magnetically insulated transmission line oscillator: Simulation and experiment

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A novel magnetically insulated transmission line oscillator (MILO) in which a modified HEM_{11} mode is taken as its main interaction mode (HEM_{11} mode MILO) is simulated and experimented in this paper. The excitation of the oscillation mode is made possible by carefully adjusting the arrangement of each resonant cavity in a two-dimensional slow wave structure. The special feature of such a device is that in the slow-wave-structure region, the interaction mode is HEM_{11} mode which is a TM-like one that could interact with electron beams effectively; and in the coaxial output region, the microwave mode is TE_{11} mode which has a favourable field density pattern to be directly radiated. Employing an electron beam of about 441 kV and 39.7 kA, the HEM_{11} mode MILO generates a high power microwave output of about 1.47 GW at 1.45 GHz in particle-in-cell simulation. The power conversion efficiency is about 8.4 % and the generated microwave is in a TE_{11}-like circular polarization mode. In a preliminary experiment investigation, high power microwave is detected from the device with a frequency of 1.46 GHz, an output energy of 43 J–47 J, and a pulse duration of 44 ns–49 ns when the input voltage is 430 kV–450 kV, and the diode current is 37 kA–39 kA.

Keywords: high power microwave, magnetically insulated transmission line oscillator, asymmetric mode, HEM_{11} mode

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1. Introduction

A magnetically insulated transmission line oscillator is a kind of gigawatt level[1−6] cross-field device that needs no external magnetic field to insulate the electrons. The magnetic field is provided by its inner current. So this device is compact, lightweight and is usually a preferred device in compact and miniaturized high power microwave (HPM) systems. In the last two decades, significant research effort was devoted to increasing the output power and pulse length.[5−8]

The traditional magnetically insulated transmission line oscillator (MILO) is a cylindrically symmetric device that usually is designed to excite the TM_{00} mode in a coaxial disk loaded slow wave structure. Because of the unfavourable electric field intensity pattern of this mode, a mode converter is usually inserted between the tube and the radiated antenna.[9,10] However, a mode converter is never 100% efficient and the introduction of the mode converter increases the length, weight, and complexity of the HPM system.

To develop a more compact system, a MILO which oscillates at HEM_{11} mode would be helpful; and a model of this particular MILO has been presented in Refs. [11] and [12]. In this type of MILO, a TE_{11} mode microwave could be generated directly in the coaxial output region so that a mode converter is not required.

Actually, due to slight asymmetry of the structure, asymmetric emission of the beam, or both, higher asymmetric modes might develop and result in mode competition. This is not a normal operation status, for the output is unstable, the power level is low, and the spectra and modes of the output microwave are usually uncontrollable. In the previous model,[11,12] the HEM_{11} mode oscillation is made possible by tuning the cavity depth of each resonant cavity in the one-dimensional (1D) slow wave structure (SWS) along the axial direction, and it has been proved experimentally. Nevertheless, particle-in-cell (PIC) simulations could not give out an HEM_{11} mode oscillation result and take account for the experimental results. To make the design of the HEM_{11} mode MILO more reliable and practical, further studies on

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the field distributions of the lowest few modes in the coaxial disk loaded SWS were carried out and an improved model[13] was developed.

According to Ref. [11], the HEM_{11} mode is the first asymmetric mode in the SWS region. It is a TM-like mode that can interact with the electrons as a TM_{00} mode wave can do. To make the HEM_{11} mode the only oscillation mode, some mode selection method must be introduced to depress the potential competition mode: TM_{00} mode. Fortunately, as an asymmetric mode, the HEM_{11} mode could be easily distinguished from the TM_{00} mode by its azimuthal polarization character. According to this idea, a two-dimensional (2D) SWS is built up to obtain a circularly polarized HEM_{11}-like mode in this paper. In this azimuthally nonsymmetrical SWS, the coupling of the TM_{00}-like mode between neighbouring cavities is much more difficult than that of the HEM_{11} mode so that the HEM_{11} mode becomes the main working mode.

The rest of the present paper is organized as follows. In Section 2, a brief introduction of the model is given. Simulation results are presented in Section 3. Some preliminary experiment results are given in Section 4, and the conclusions are drawn from the present study in Section 5.

2. Brief introduction of the SWS

Based on the traditional 1D coaxial disk loaded SWS, a 2D SWS could be constructed by introducing some kind of asymmetry in the azimuthal direction. A simple way is to azimuthally divide the 1D SWS into several partitions, as in Refs. [14]–[16]. The cavity used in this paper is illustrated in Fig. 1. It has the same structure parameters as those in Refs. [14]–[16], but its queuing discipline is different from those, which is shown in Fig. 2. In this configuration, the cavities are arranged in a stepwise sequence in which each cavity has a 90° shift in an azimuthal direction from its upstream neighbour. Analogous with the double period SWS used in a rising-sun magnetron, the model we built is a four-period SWS. In the four-period SWS, the excitation of the TM_{00} mode is extremely difficult because symmetry boundary condition no longer exists. Contrarily, this structure is suitable for an HEM_{11} mode because it could be in a circular polarized status in this structure.

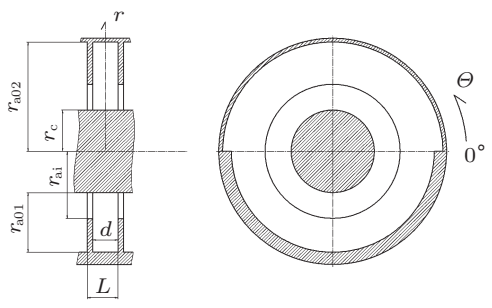


Fig. 1. Schematic plot of the 2D coaxial disk loaded slow wave structure.

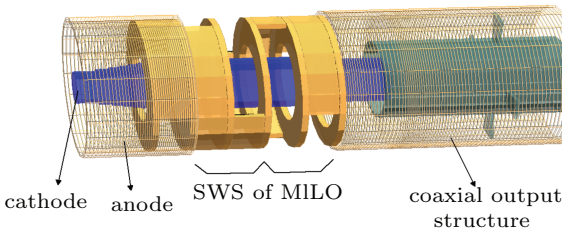


Fig. 2. (colour online) Configuration of a modified HEM_{11} mode MILO: the anode outside the SWS region ($r > r_{ao2}$) is removed to obtain a better view of the SWS.

3. PIC simulation

To test the validity of our theoretical analysis, an HEM_{11} mode oscillating MILO adopting the newly designed SWS is simulated by 3D PIC code.

Figure 3 shows the output power of the tube, corresponding beam parameters are 441 kV and 39.7 kA. The average output power is about 1.47 GW, corresponding to a power efficiency of 8.4%. Figure 4 shows the frequency spectrum and a time-frequency analysis of the output microwave. We can see that the oscillation frequency is 1.45 GHz, the main frequency starts at about 12 ns, and is saturated at about 20 ns. Before 10 ns, there are some signals with other frequencies. These unexpected signals in each cavity cannot couple with each other, and they decay rapidly as the main frequency signal arises.

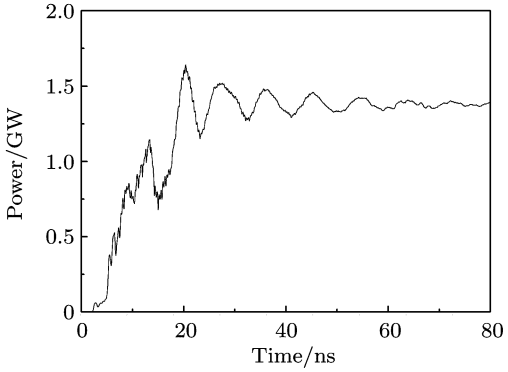


Fig. 3. Output power of the modified HEM_{11} mode oscillating MILO.

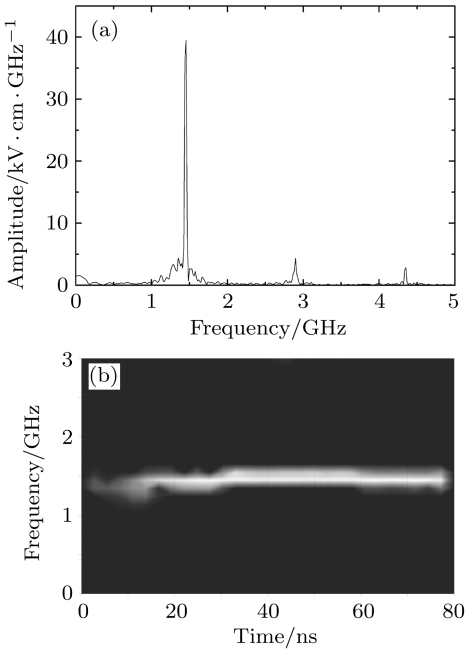


Fig. 4. Frequency spectrum (a) and frequency-time analysis (b) of output microwave signal.

Figure 5 illustrates the field patterns at the output port at different times. We can see from the field patterns that the output microwave has a TE_{11}-like distribution and it is circular polarized, the rotation direction is right-handed; the rotation period is about 0.7 ns, corresponding to the oscillation frequency 1.45 GHz.

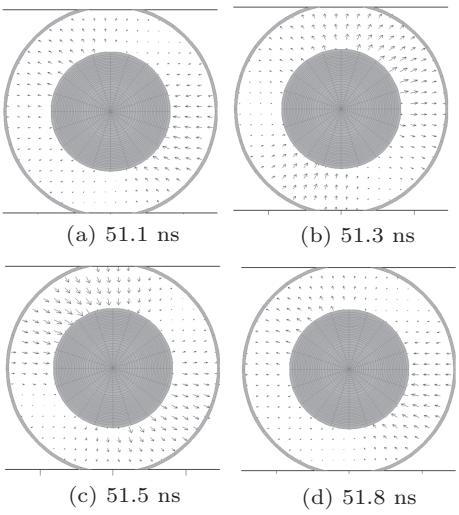


Fig. 5. Electric field patterns at the output port at times of 51.1 ns (a), 51.3 ns (b), 51.5 ns (c), and 51.8 ns (d).

Additionally, if we change the arrangement of each cavity to obtain an inverse chain of the HEM_{11} mode MILO, the polarized direction of the output microwave will turn left-handed.

4. Preliminary experiment

A preliminary experiment is carried out on the HEM_{11} mode MILO, which is fabricated according to the high frequency analysis. A 600-mm diameter radiation antenna which is designed for another high power MILO system[17] is used to facilitate the preliminary experiment. The device is driven by a set of power adjustment equipment in our laboratory. The entire apparatus is pumped down to a pressure of approximately 2×10^{-2} Pa. An L band calorimeter is placed near the radiation antenna to measure the radiation energy, as shown in Fig. 7. The calorimeter consists of a wide-aperture microwave-absorbing load, a control and registration unit and a calibrator.

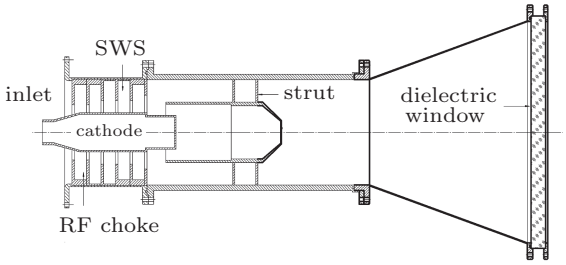


Fig. 6. HEM_{11} mode MILO experiment system.

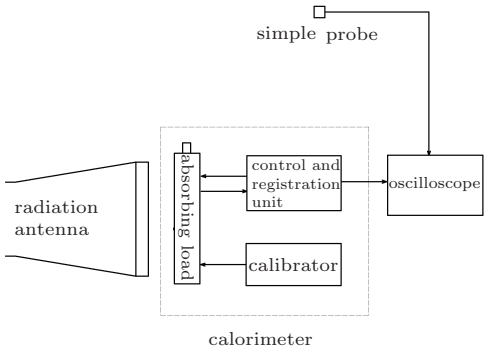


Fig. 7. Schematic plot of the energy measurement system.

A radio-frequency head with a leading-out wire is used as a simple probe to detect the microwave frequency. The signal from the simple probe is transmitted by the attenuating cable to a shielding room, attenuated by fixed coaxial attenuators, and then transmitted to the oscilloscope.

4.1. Microwave frequency

Figure 8 shows the simple probe signal from an oscilloscope of Lecory 8600A, associated with its spectrum. The microwave frequency is measured to

be 1.46 GHz. The measured frequency ranges from 1.45 GHz to 1.47 GHz from shot to shot, agree well with the simulation result.

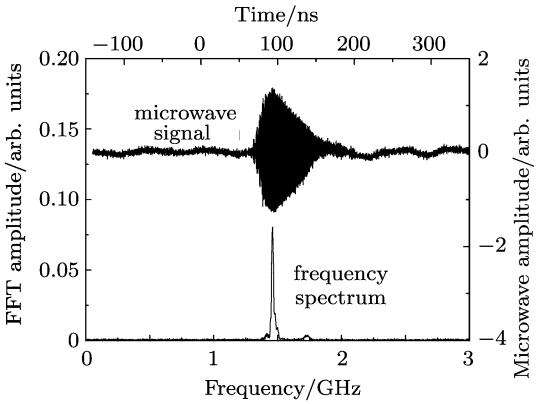


Fig. 8. Detected microwave signal and its spectrum.

4.2. Microwave pulse width

The pulse width could be read out from the oscilloscope; it ranges from 44 ns to 49 ns.

4.3. Microwave energy

The microwave absorbing load is filled with ethyl alcohol mixture and connects to a capillary tube sensor. The operation of the calorimeter is based on the expansion of alcohol due to its temperature increase when the microwave energy is absorbed in the alcohol volume. The expansion of alcohol is determined through measuring the displacement of the alcohol meniscus in the capillary tube.

Energy test results are listed in Table 1. When the diode voltage ranges from 430 kV to 450 kV, microwave pulse energy ranges from 43 J to 47 J.

Table 1. Detected microwave energy in experiment.

No.	V/kV	I/kA	E/J	FWHM / ns
1	448	38.5	46	48
2	450	39	43	44
3	430	37.6	47	49

4.4. Power density distribution

To verify the directional radiation ability of the HEM_{11} mode MILO, the far-field power density distribution of the tube is measured qualitatively. The measurement system is shown in Fig. 9. To avoid breakdown, some S-band (2.6 GHz–3.95 GHz) open waveguides (BJ-32) are used as microwave signal receivers.

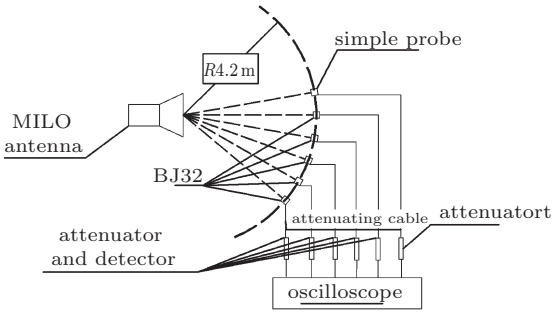


Fig. 9. Schematic plot of the far-field measurement system.

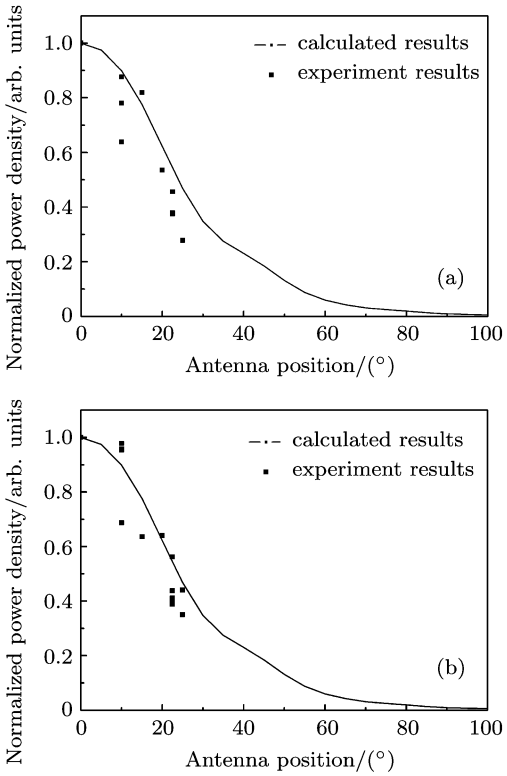


Fig. 10. Normalized power density distributions in far-field for (a) all BJ-32 waveguides that are in perpendicular polarization and (b) all BJ-32 waveguides that are in horizontal polarization.

For an HEM_{11} mode MILO shown in Fig. 6, the polarization of the radiated microwave is unpredictable before experiment. It varies from one shot to another. Our measurement is based on the superposition theorem that an arbitrary polarized electromagnetic wave could be decomposed into two orthogonal linear polarized waves. By changing the polarization of BJ-32 waveguides, both of the polarized components are measured as shown in Fig. 10. We can see

that the power density variation tendency is well consistent with the calculated radiation pattern of TE_{11} mode.

5. Conclusions

Based on a deeper understanding of the high frequency characteristics of a 2D SWS, the arrangement of each cavity is carefully adjusted, and new SWS with a circular polarized HEM_{11}-like resonant mode is designed. An HEM_{11} mode MILO in which this SWS is adopted is simulated through PIC code. Employing an electron beam of 441 kV and 39.7 kA, a microwave output of 1.47 GW is obtained. The power conversion efficiency is about 8.4%, and the microwave frequency is 1.45 GHz. The microwave is right-hand polarized with a rotation period of about 0.7 ns; corresponding rotation frequency is the same as the oscillation frequency. The rotation direction can be changed by changing the rotation direction of the SWS.

A preliminary experiment is carried out to test the performance of the tube. The frequency, pulse width, pulse energy, and radiation power density distribution of the radiation microwave are measured. When the diode voltage ranges from 430 kV to 450 kV and the diode current ranges from 37 kA to 39 kA, high power microwave is detected from the device with a frequency of 1.46 GHz: its output energy is 44 J–49 J per pulse, and pulse duration is 44 ns–49 ns. The power density distribution in far-field of the radiation microwave is consistent with the calculated radiation pattern of TE_{11} mode qualitatively.

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