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Magnetically insulated transmission line oscillator oscillated in a modified HEM_{11} mode*

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This paper puts forward a novel magnetically insulated transmission line oscillator (MILO) for the first time which takes a modified HEM_{11} mode as its main interaction mode. The excitation of the oscillation mode is made possible by carefully adjusting the arrangements of each resonant cavity in a two-dimensional (2-D) slow wave structure. The high frequency characteristics are analyzed and a PIC simulation is carried out; the detailed results are discussed to get a better understanding of this new MILO. Employing an electron beam of about 441 kV and 39.7 kA, it finds that the modified HEM_{11} mode MILO generates a high power microwave output of about 1.47 GW at 1.45 GHz. The power conversion efficiency is about 8.4% and the generated microwave is in a TE_{11}-like circularly polarized mode; its polarization direction is decided by the rotation direction of the SWS.

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

PACC: 4110H, 4190, 2900

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 directed in increasing the output power and pulse length.[5−8]

The traditional magnetically insulated transmission line oscillator (MILO) is a cylindrically symmetric device which is usually designed to excite the TM_{00} mode in a coaxial disk loaded slow wave structure. Because of the unfavorable 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 new 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 the slight asymmetry of the structure, asymmetric emission of the beam, or both, higher asymmetric modes might develop and result in modes competition. This is not a normal operation status, for the output is unstable, the power level is low, and the lifetime of the cathode is usually shortened. So the uniformity of the electrostatic field must be ensured in designing an HEM_{11} mode working MILO, such as the model used in Refs.[11] and [12]. But the selection of HEM_{11} mode by tuning cavity depth of each resonant cavity in the 1-D SWS has only been proved in simulation without electrons. Although the experimental results are consistent with the high frequency analysis, PIC simulations could not give out an HEM_{11} mode microwave. To make HEM_{11} mode the main oscillation mode in PIC simulation, some other mode selection methods must be introduced to depress the lowest symmetric mode. This would also make the design more reliable and practical.

According to Ref.[11], HEM_{11} mode is a TM-like mode in the slow wave structure (SWS) region

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that could interact with the electrons in a similar way as well as a TM_{00} mode wave. The only difference between these two modes is that HEM_{11} mode has a nonzero azimuthal wave number. Utilizing the azimuthal characteristic of HEM_{11} mode, this paper builds up a two-dimensional (2-D) SWS to obtain a circularly polarized HEM_{11}-like mode, and in this azimuthally nonsymmetrical SWS, the coupling of TM_{00}-like mode between neighboring cavities is much more difficult than HEM_{11}-like mode. Section 2 gives out a basic discussion of a single cavity in the 2-D SWS. Modeling and analyzing of the high frequency characteristics of the coupled resonant cavity chain is arranged in Section 3. Section 4 gives out some PIC simulation results to test the design, and conclusions are presented in Section 5.

2. Basic discussion of a single cavity

Based on the traditional one-dimensional (1-D) coaxial disk loaded SWS, 2-D SWS could be constructed by introducing some kind of asymmetry in the azimuthal direction. A simple way is to azimuthally divide the 1-D SWS into several partitions, such as that in Refs.[13]–[17]. The cavity used in this paper is illustrated in Fig.1. It has the same structure parameters as those in Refs.[13]–[15], but the queuing discipline is different, which will be discussed in the third section.

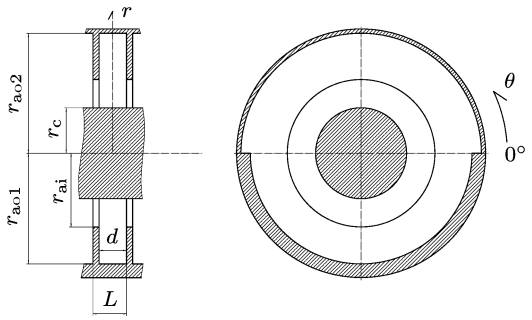


Fig.1. Schematic diagram of the 2-D coaxial disk loaded slow wave structure.

Imaging an axial periodicity of this cavity, we can derive the eigenfunction in a quite familiar way as that in Refs.[11] and [12], and the dispersion curves are illustrated in Fig.2(a), as well as the dispersion curves of a corresponding 1-D SWS shown in Fig.2(b).

We can see from Fig.2(b) that, in a azimuthally symmetrical system, the lowest curve represents the azimuthally uniform TM_{00} mode; mode 2 and mode 3 are degenerate, representing HEM_{11} mode; mode 4 and mode 5 are degenerate, representing HEM_{21} mode.

However, in an azimuthally nonsymmetrical system, because of the lost of uniformity in the azimuthal direction, originally degenerated HEM_{11} mode and HEM_{21} mode split into two separate modes respectively, as shown in Fig.2(a). And even the lowest mode is different from that in Fig.2(a), for its longitudinal magnetic field has a modified distribution like a TE_{11} mode.

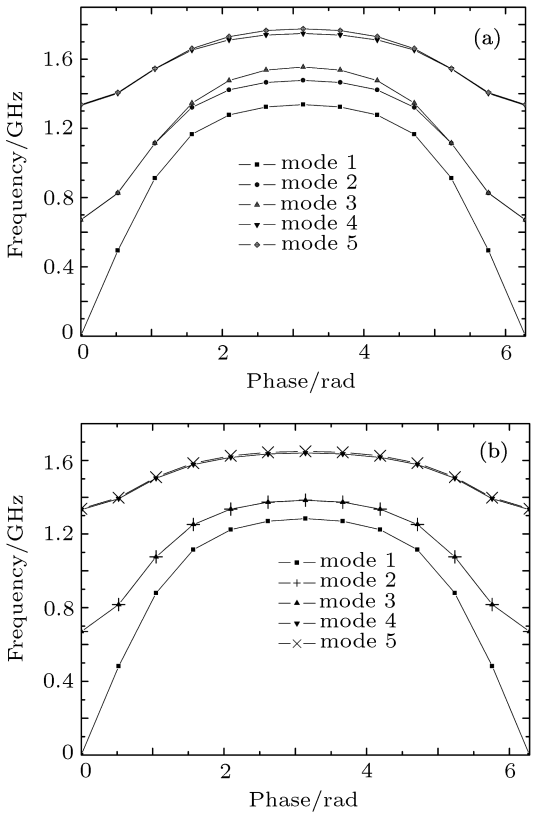


Fig.2. Typical dispersion curves: r_c=53 mm, r_{ai}=86 mm, d=22 mm, L=27 mm. (a) Azimuthally nonuniform system: r_{ao1}=129 mm, r_{ao2}=140 mm; (b) Azimuthally uniform system: $r_{ao1} = r_{ao2}$=140 mm.

Figures 3-5 are the field distributions of the first three modes in Fig.2(a). We can see from Fig.3 that the electromagnetic field of mode 1 mainly located in the azimuthal partition of 0°–180°; analogously, mode 3 has an electromagnetic field mainly located in the azimuthal partition of 180°–360°, as shown in Fig.5. Being different from these two modes, mode 2 has a field distribution with the field mainly located in the boundary region between mode 1 and mode 3.

In a former bifrequency MILO (BFMILO) configuration,[13−16] mode 1 and mode 3 are treated as

the basic modes in the azimuthal partitions of 0°–180° and 180°–360° respectively; mode 2 is ignored for its inappropriate field distribution. But in this paper, we are going to construct a new configuration that would take mode 2 as its main oscillation mode. Because this particular mode has an analogous field distribution with an HEM_{11} mode in an azimuthally uniform system, mode 2 is also named as the modified HEM_{11} mode hereafter.

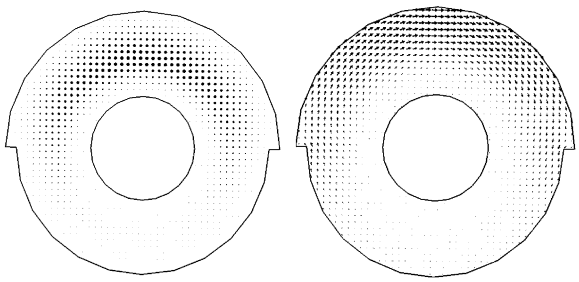


Fig.3. Field distribution of mode 1: left-electric, right-magnetic.

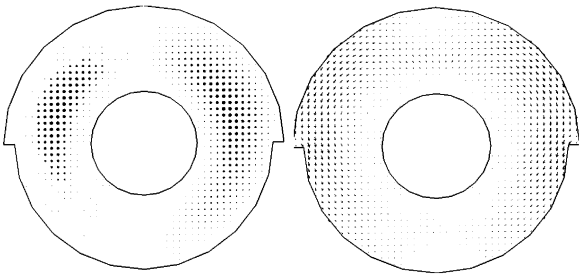


Fig.4. Field distribution of mode 2: left-electric, right-magnetic.

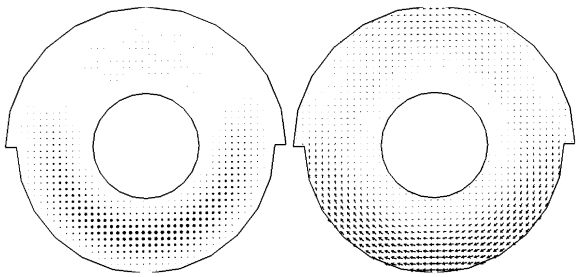


Fig.5. Field distribution of mode 3: left-electric, right-magnetic.

3. Modeling and high frequency analysis

Being different from a bifrequency MILO, here mode 1 and mode 3 are unexpected microwave modes in a modified HEM_{11} mode MILO. How to depress the coupling of mode 1 and mode 3 between neighboring cavities and make mode 2 the oscillation mode? Easily we come to a configuration as shown in Fig.6.

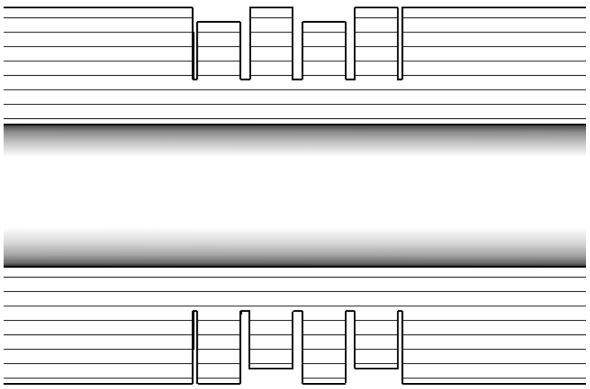


Fig.6. Configuration of a non-BFMILO SWS.

In this configuration, we rotate each cavity 180° away in the azimuthal direction from its upstream neighbor to destroy the coupling of mode 1 and mode 3 as in a BFMILO. But this configuration is still hard to obtain a mode 2 oscillation because that, although mode 1 and mode 3 could be depressed, an unexpected double period SWS like the rising-sun geometry used in a magnetron forms. In this double period SWS, a TM_{00}-like mode with an eigen-frequency between mode 1 and mode 3 becomes the new oscillating mode, as shown in Fig.7.

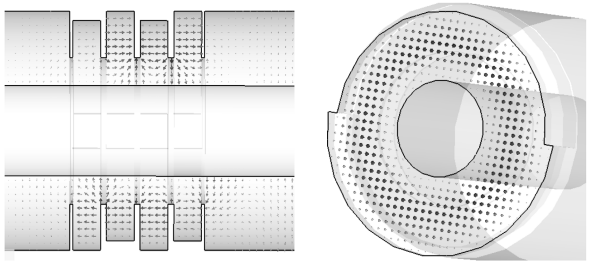


Fig.7. TM_{00}-like field distribution: left-z–r plane, right-r–θ plane.

To obtain an asymmetric mode oscillation, the configuration shown in Fig.6 must be modified. If we rotate the cavities only 90° away from each other, a new resonant cavity chain will be achieved, as shown in Fig.8. In this new configuration, the unexpected double period SWS could be destroyed, and because every cavity is moved 90° away from each other, the coupling of mode 1 and mode 3 as that in a BFMILO is also largely depressed. Contrarily, this structure brings only a little influence to mode 2, because that is

an HEM_{11}-like mode, mode 2 could be created in this new configuration under a circularly polarized status.

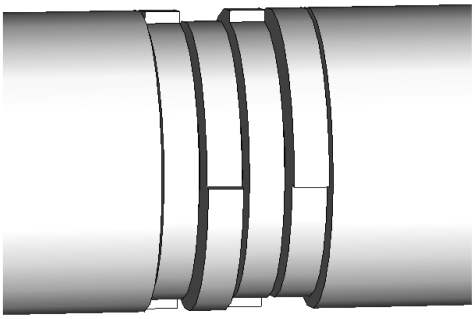


Fig.8. Configuration of a modified HEM_{11} mode MILO SWS.

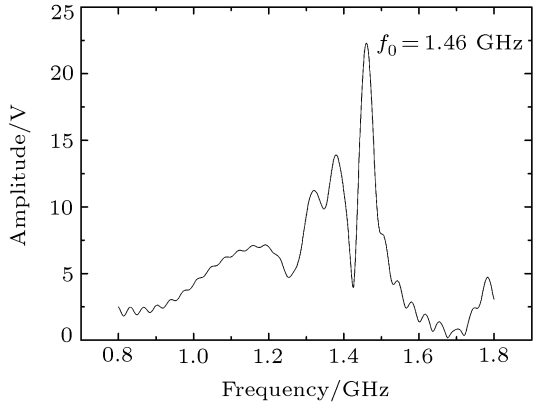


Fig.9. Frequency response of the SWS.

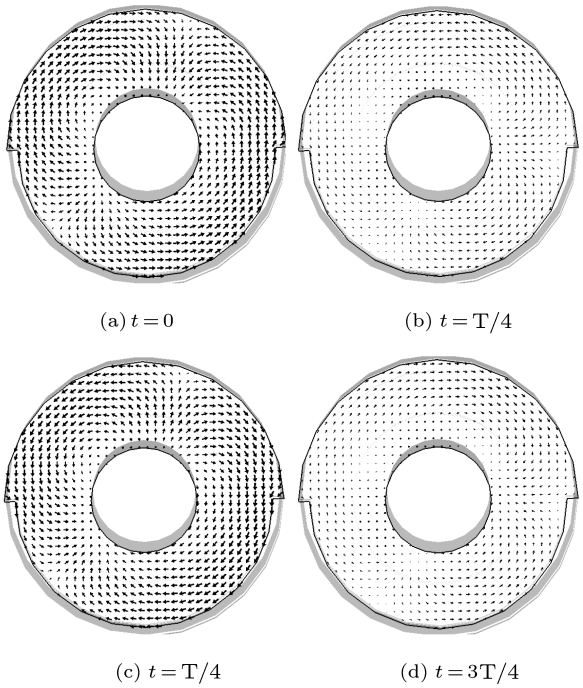


Fig.10. Magnetic field distribution in a cavity in r–θ plane.

Figure 9 is the frequency response of SWS to a TEM wave. The calculation is carried out by a FIT (finite integral technique) simulation code, both the two ends along the axial direction are set to be waveguide ports. We could see that the main resonant frequency is 1.46 GHz; the resonant microwave is mode 2, as shown in Fig 10. From the field distribution at different times, we could see that the resonant microwave mode is in a right-handed circularly polarized status. This configuration agrees with the requirements of the design.

4. PIC simulation and discussion

To test the validity of our theoretical analysis, an HEM_{11} mode oscillating MILO adopting the newly designed SWS is simulated by a three-dimensional PIC code. Figure 11 shows the output power of the tube, corresponding beam parameters are 441 kV and 39.7 kA. The large portion of the DC component in the instantaneous power reveals that the output microwave is mainly constituted of a circularly polarized signal. The average output power is about 1.47 GW, corresponding to a power efficiency of 8.4%.

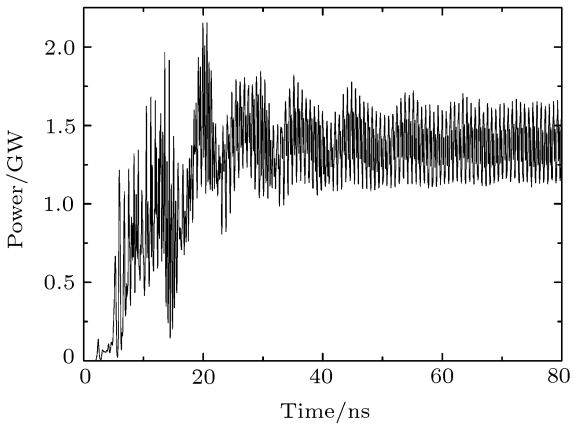
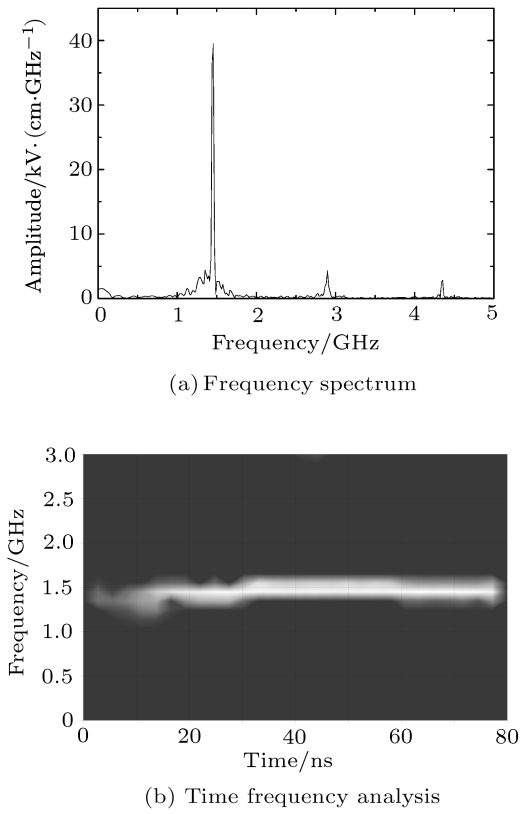


Fig.11. Output power of the modified HEM_{11} mode oscillating MILO.

Figure 12 shows the frequency spectra and a time-frequency analysis of the output microwave. We could see that the oscillation frequency is 1.45 GHz, is consistent with the high frequency analysis. The main frequency started at about 12 ns, and is saturated at about 20 ns. Before 10 ns, there are some signals with other frequencies, but these unexpected signals

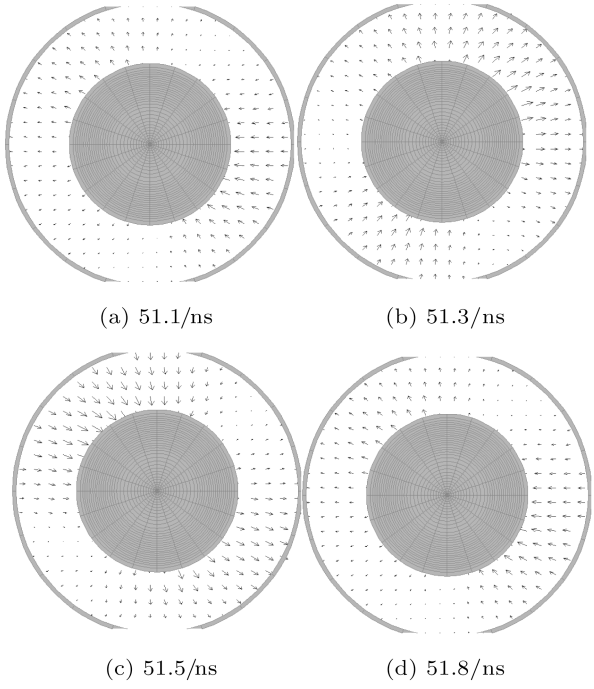
in each cavity cannot match each other, and they decay rapidly as the main frequency signal arises.



(a) Frequency spectrum

(b) Time frequency analysis

Fig.12. Data analysis of output microwave signal.

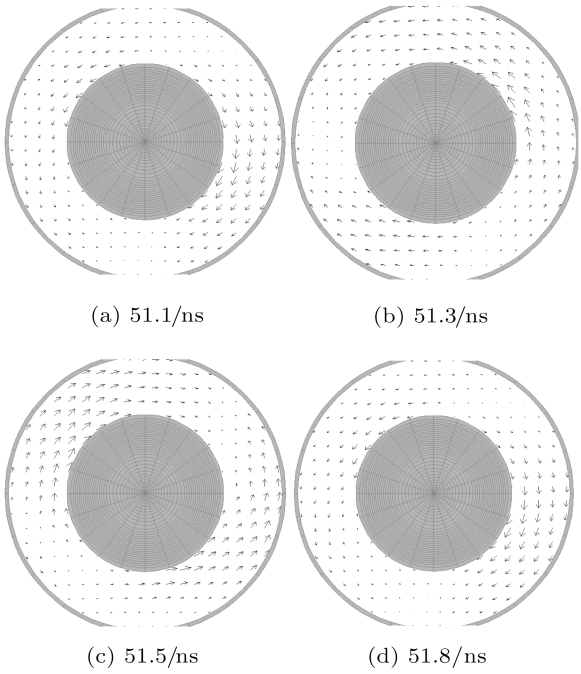


(a) 51.1/ns (b) 51.3/ns

(c) 51.5/ns (d) 51.8/ns

Fig.13. Electric field pattern at the output port.

Figures 13 and 14 illustrate the field patterns at the output port at different times. We can see from the field pattern that the output microwave has a TE_{11}-like distribution. And it is circularly polarized, the rotation direction is right-handed, the rotation period is about 0.7 ns, corresponding to the oscillation frequency. These results are consistent with the high frequency analysis.



(a) 51.1/ns (b) 51.3/ns

(c) 51.5/ns (d) 51.8/ns

Fig.14. Magnetic field pattern at the output port.

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

5. Conclusions

Based on a deeper understanding of the high frequency characteristics of a 2-D SWS, the arrangements of each cavity are carefully adjusted, and a new SWS with a circularly polarized HEM_{11}-like resonant mode is designed. The high frequency characteristics of this new SWS is analyzed and a modified HEM_{11} mode oscillating MILO adopting this SWS is simulated by PIC code. Employing an electron beam of 441 kV, 39.7 kA, we obtain a microwave output of 1.47 GW. The power conversion efficiency is about 8.4%, and the microwave frequency is 1.45 GHz. The microwave is right-handed polarized with a rotation

period of about 0.7 ns, the corresponding rotation frequency is the same as the oscillation frequency. The rotation direction could be changed by changing the rotation direction of the SWS.

The concept of HEM_{11} mode MILO breaks the traditional design considerations based on the fundamental mode. Both theoretical analysis and PIC simulation results show that we could output pure TE_{11}-like mode directly in MILO without the help of a mode converter. Nevertheless, the power efficiency of this new MILO is somewhat less than a traditional one, some more optimization effort should be directed in it. The research might benefit the further studies of miniaturization and compactness of MILO system.

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