Miniaturized Metamaterial-based Sheet Beam Radiation Sources

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Abstract: *In this paper, we investigate the transmission characteristics of metamaterial (MTM) -based slow-wave structure (SWS) with two waveguide couplers by using the frequency domain solver in CST 2016 Microwave Studio. The radiation source is also presented here based on the above structure to study the beam-wave interaction verified by the particle-in-cell (PIC) in CST 2016 Particle Studio. The simulation results show that the MTM-based SWS has a pass band near 3 GHz. Meanwhile, the radiation source has electronic efficiency of 26.7% and its peak output power is 61.6 kW at 2.83 GHz when the beam voltage and beam current are 38.5 kV and 6 A, respectively. The characteristic of miniaturization is shown by the fact that the transverse dimension of the MTM-based SWS is approximately 1/7 to 3/7 of the corresponding S band conventional structure***.**

Keywords: transmission characteristics, metamaterial (MTM), slow-wave structure (SWS), beam-wave interaction, miniaturization

Introduction

Metamaterials (MTMs) are a kind of artificial composite materials with sub-wavelength characteristics that exhibit unique electromagnetic properties usually not found in natural. In recent years, a lot of applications have been studied based on MTMs, such as antennas, invisible cloaks and absorbing materials. Moreover, the MTMs have great potential in vacuum electron devices (VEDs) due to their unique electromagnetic properties [1, 2]. When operating below the cut-off frequency of the main transverse magnetic (TM) mode, the waveguide can provide negative permeability. The complementary electric split ring resonators (CeSRRs) can provide negative permittivity in a certain frequency range. So, the CeSRR array can be loaded into the waveguide to construct metamaterial whose permittivity and permeability are both negative. For example, the MTM-loaded waveguides can be treated as novel slow wave structures with high interaction impedance and MTM-loaded waveguides can achieve all-metal structures to avoid the influence of supporting media on device performance.

In this paper, we simulate the transmission characteristics of the MTM-based SWS by using the frequency domain solver in CST 2016 Microwave Studio and the beam-wave interaction of the sheet beam radiation source based on the above MTM-based SWS by using the particle-in-cell (PIC) solver in CST 2016 Particle Studio.

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Transmission characteristics simulation

The simulation model is shown in Figure 1 [3]. It includes an MTM-based slow-wave structure (SWS) and two rectangular waveguide couplers. The MTM-based SWS consists of 8 CeSRR unit cells and a square waveguide. The CeSRR is first proposed in [4] with the period of 14.5 mm and thickness of 1.2 mm. Compared with the conventional devices, this device has the characteristic of miniaturization due to the sub-wavelength property of CeSRR and the fact that the empty square waveguide operates below the cutoff frequency. The transverse dimension of MTM-based SWS is much less than the free space wavelength of its operating frequency. Two waveguide couplers are added to the two ends of the SWS in order to study the transmission of frequency signal in the structure. In order to get better energy output, the MTM is extended into the rectangular waveguide of a fixed length. Two probes are connected to each end of the CeSRR unit cell and inserted into the waveguide by means of probe excitation. At this time, the probes form small radiation antennas inside the waveguides, which radiate microwave energy from the SWS into the waveguide and establish the required working mode in the waveguide. The difference between the two waveguide couplers is that one of the waveguide coupler has one more reserved sheet beam channel than the other waveguide coupler. A good match between the SWS and the waveguide is achieved by optimizing the structure.

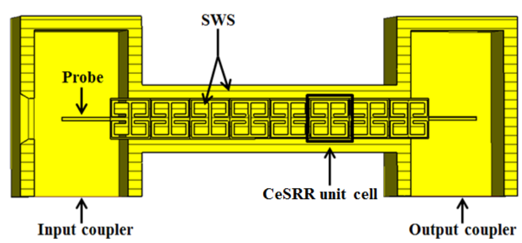

Fig. 1. MTM-based SWS with waveguide couplers.

We calculate the transmission characteristics of MTM-based SWS and the results are shown in Figure 2. As can be seen from the figure, the structure has a pass band near 3 GHz in the double negative band of the MTM-based SWS. The simulation results show that the waveguide couplers can transmit the signal effectively. The transverse dimension of the SWS is approximately $\lambda/7$ (λ is wavelength in the free space of the operating frequency), while the transverse dimension in conventional structure is about $\lambda/3$ to λ [5].

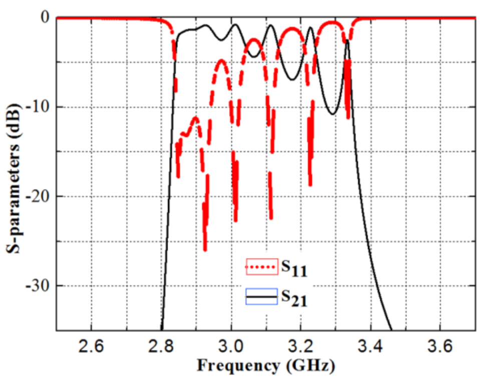

Fig. 2. Simulation results of transmission characteristics.

Beam-wave interaction simulation

In the next, we propose an MTM-based sheet beam radiation source and the simulation model is shown in Figure 3. It is clear from the figure that the radiation source includes cathode, waveguide coupler, SWS and collector. In the simulation, an ideal electron emission surface is used to replace the electric gun and the shape of the cathode is rounded rectangle to generate the sheet beam as the electron source. The width and height of the cathode emission surface is 12 mm and 2 mm respectively. Compared with [3], the sheet beam voltage and current are reduced to 38.5 kV and 6 A, respectively. Meanwhile, the axial magnetic field B_z of 0.5 T is used to focus the sheet beam and the distance between sheet beam and CeSRR array is 0.5 mm.

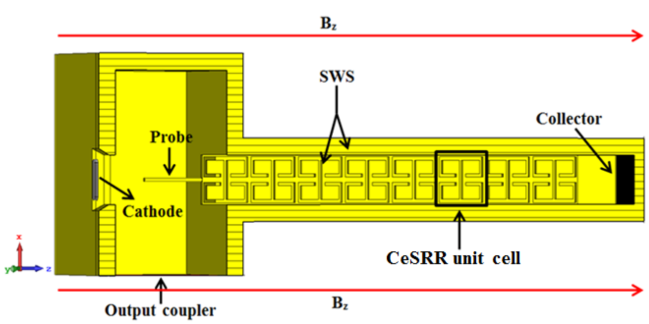

Fig. 3. Simulation model of MTM-based sheet beam radiation source.

Based on the above analysis, we simulate the performance of the sheet beam radiation source. As shown in Figure 4, with the varying time, the average output power of the signal generated by this radiation source tends to be stable after 160 ns. Figure 5 shows that the operating frequency is 2.83 GHz and the peak output power reaches 61.6 kW. The electronic efficiency of the radiation source at this stage is about 26.7%. We can also see that high frequency oscillation is generated at the frequency of 4.45 GHz, which will be improved and eliminated in the following research work.

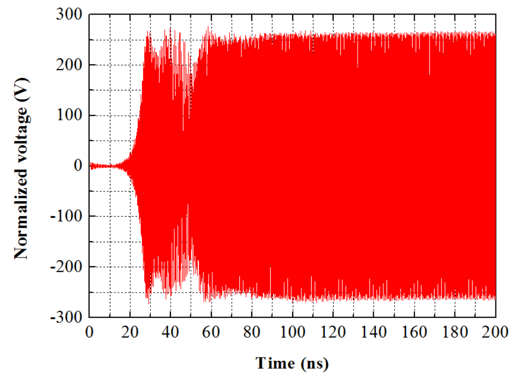

Fig. 4. The normalized voltage versus with time.

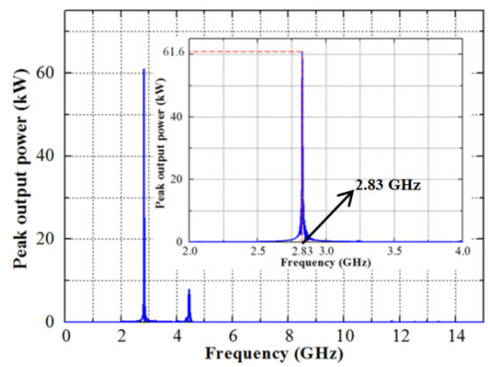

Fig. 5. The peak output power versus with frequency.

Conclusion

The simulation of transmission characteristics and beam-wave interaction in the miniaturized sheet beam device has been carried out. The results show that this device has the characteristics of effective transmission and high efficiency. Moreover, the transverse dimension of the slow-wave structure is approximately 1/7 to 3/7 of the corresponding S band conventional devices. This work can lay the foundation for developing novel vacuum devices based on MTMs in the future.

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