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A compact dual-band radiation system*

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Complex magnetically insulated transmission line oscillator (MILO), as an important development direction, can enhance the power efficiency and generate dual-band high power microwaves (HPMs). A complex MILO and a preliminary dual-band radiation system have been proposed in our previous studies. However, the axial length of the dual-band radiation system is too long to meet the compact requirements. In this paper, a compact dual-band radiation system is presented and investigated numerically. The compact dual-band radiation system comprises a dual-band cross-shaped mode converter and a dual-band coaxial conical horn antenna. It can convert two coaxial TEM mode microwaves (1.717 GHz and 4.167 GHz) generated by the complex MILO into the coaxial TE_{11} mode microwaves, and then radiate them into the air. At 1.717 GHz, the gain of the antenna is 17.9 dB, and the total return loss and diffraction loss are 1.50% and 0, respectively. At 4.167 GHz, the gain is 19.4 dB, and the total return loss and diffraction loss are 1.17% and 0.78%, respectively. The power handling capacity of the antenna is 5.1 GW at 1.717 GHz and 2.0 GW at 4.167 GHz. Comparing with the original structure, the length of the dual-band radiation system is reduced by 45.2%.

Keywords: dual-band, mode conversion antenna, high power microwave (HPM)

PACS: 84.90.+a, 84.40.Fe **DOI:** 10.1088/1674-1056/aba607

1. Introduction

Of all the high power microwave sources, the magnetically insulated line oscillator (MILO) is considered as one of the most promising HPM devices,[1–16] which has the advantages of high power, stable operation, no external magnetic field, compact structure, *etc*. However, the power efficiency of MILO is not so high because some intense electron beams are required to generate an insulating magnetic field.

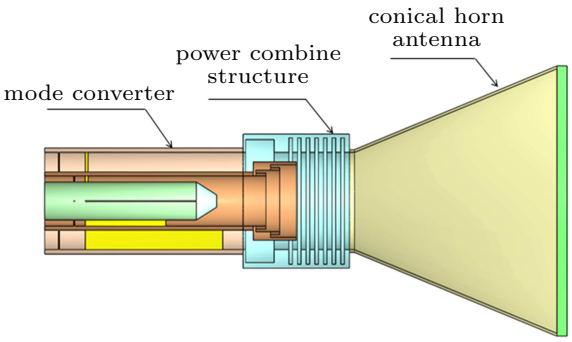


Fig. 1. Preliminary dual-band radiation system.

To enhance the power efficiency and generate dual-band HPM, a complex MILO and a preliminary dual-band radiation system have been proposed[11,17] as shown in Fig. 1. The complex MILO is redesigned and it can generate dual-band TEM microwave of 1.717 GHz with the power of 8.3 GW and 4.167 GHz with the power of 4.0 GW in simulation. Considering the limitation of the experimental condition, the anticipative output power are about 4.15 GW at 1.717 GHz and 2.0 GW at 4.167 GHz in the intending experiments. The dual-band radiation system comprises a coaxial plate-inserted mode converter, a power combiner, and a conical horn antenna. However, its axial dimension is 997 mm, which is too long to meet the compact requirements.

2. Structure and design

The whole structure of the compact dual-band radiation system is illustrated in Fig. 2. It consists of a dual-band cross-shaped mode converter and a dual-band coaxial conical horn. The former converts the coaxial dual-band TEM mode into coaxial TE_{11} mode, and the latter radiates the coaxial TE_{11} mode directionally. The cross-shaped mode converter comprises an input coaxial circular waveguide, four rectangular waveguides (RWG) whose lengths are different, and an output coaxial circular waveguide. The dual-band coaxial conical horn comprises an outer conical horn, an inner conical horn, and a frustum.

Taking the low frequency band for example, the principle of the radiation system is described as follows. When passing through the four RWGs, the microwave will produce phase difference because of their different lengths. If the lengths of the four RWGs satisfy the following equations, the cross-shaped mode converter can convert the coaxial TEM mode into a coaxial TE_{11} mode:[18,19]

$$L_1 = L_2, \quad L_3 = L_4,$$
$$\Delta L = L_3 - L_1 = L_4 - L_2 = \lambda_g/2,$$

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$$\lambda_g = \lambda_0 / \sqrt{1 - (\lambda_0/2a)^2}, \tag{1}$$

where L_1, L_2, L_3, and L_4 are the lengths of four RWGs, λ_g is the waveguide wavelength in the RWG, ΔL is the difference in length between the RWGs, a is the width of the rectangular waveguide, and λ_0 is the wavelength in free space.

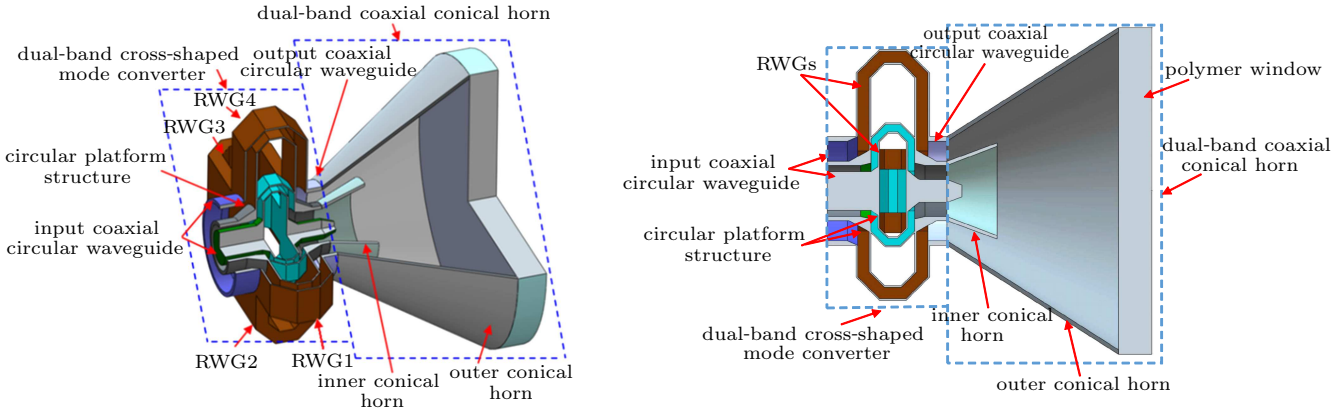


Fig. 2. Structure of compact dual-band radiation system.

In order to achieve a pure TE_{10} mode microwave and prevent undesired high-order modes (such as TE_{11}, TM_{11}, and TE_{30} modes) in the rectangular waveguide, the operation wavelength of microwave should be higher than that of TE_{30} mode and lower than that of TE_{10} and TE_{01} modes, that is

$$\begin{cases} \lambda_{cTE30} < \lambda_0 < \lambda_{cTE10}, \\ \lambda_0 < \lambda_{cTE01}, \end{cases} \tag{2}$$

where λ_{cTE30}, λ_{cTE10}, and λ_{cTE01} can be obtained from the following equation:

$$\begin{aligned} \lambda_{cmn} &= \frac{2\pi}{k_{cmn}} = \frac{2\pi}{\sqrt{(m\pi/a)^2 + (n\pi/b)^2}} \\ &= \frac{2}{\sqrt{(m/a)^2 + (n/b)^2}}, \end{aligned} \tag{3}$$

and b is the height of the rectangular waveguide.

From Eqs. (2) and (3), we can obtain

$$\begin{cases} \dfrac{\lambda_0}{2} < a < \dfrac{3\lambda_0}{2}, \\ b > \dfrac{\lambda_0}{2}. \end{cases} \tag{4}$$

According to Eqs. (1) and (4), we take $a_1 = 146$ mm and $b_1 = 20$ mm at 1.717 GHz, so $\Delta L_1 = 109$ mm, and we take $a_2 = 76$ mm and $b_2 = 12$ mm at 4.167 GHz, so $\Delta L_2 = 41$ mm.

The coaxial TE_{11} mode is converted into the linear-polarized circular waveguide TE_{11} mode and radiated by the coaxial conical horn into the air. In the coaxial conical horn, the inner cone can change the field distribution in the horn and enhance the directivity.[19]

As for the selection of the size of the conical horn, because the working frequency of the conical horn is fixed and single, the finite element simulation is used to optimize the size of the conical horn. According to actual needs, the length of the outer conical horn should be less than 320 mm, finally, when $L = 298$ mm and $r = 277$ mm (L is the axial length of the conical horn and r is the caliber radius), the maximum gain is obtained at 1.717 GHz, and the inner conical horn is also optimized by this method.

Then, a compact dual-band (L-band and C-band) radiation system is designed, and the operation frequencies are 1.717 GHz and 4.167 GHz, respectively. The RWGs' axial lengths of C-band mode converter are both shorter than the shortest distance between the vertical RWGs of the L-band mode converter. Therefore, the C-band mode converter can be embedded in the L-band mode converter.

Compared with the original structure,[17] the dual-band cross-shaped mode converter replaces the dual-band plate-inserted mode converter, and the dual-band coaxial conical horn replaces the power combiner and the conical horn. The replacing can bring the following benefits:

(i) the axial length is greatly shortened;

(ii) there is no complicated corrugated structure, nor manufacturing difficulty, and cost is greatly reduced, and the power capacity of the device can also be improved.

3. Simulation and analysis

3.1. Dual-band cross-shaped mode converter

For the dual-band cross-shaped mode converter, its output mode is pure TE_{11} mode and the reflection mode is mainly TEM mode, which can meet the requirements that the mode-converter only reflects TEM mode and output pure TE_{11} mode microwave, which is convenient to eliminate reflection and high-order modes. So, there is no need of reflection matching structure in the design of mode converter.

The dual-band mode converter is established and simulated by CST STUDIO SUITE, and the injected mode is TEM

mode whose power is 1.0 W. The simulation results are shown in Figs. 3 and 4. From Fig. 3, it can be seen that the TEM mode is converted into the TE_{11} mode. The output modes are mainly TE_{11} mode at the central frequencies, and the transmission efficiencies are 96.8% (L-band) and 94.4% (C-band), respectively. The components of TEM modes and other modes are very small, and their transmission efficiencies are all less than 0.05%. The mode converter outputs the pure dual-way coaxial TE_{11} mode microwave. The reflection modes are mainly TEM mode at the central frequency, whose return-losses are 3.2% (L-band) and 5.0% (C-band), respectively.

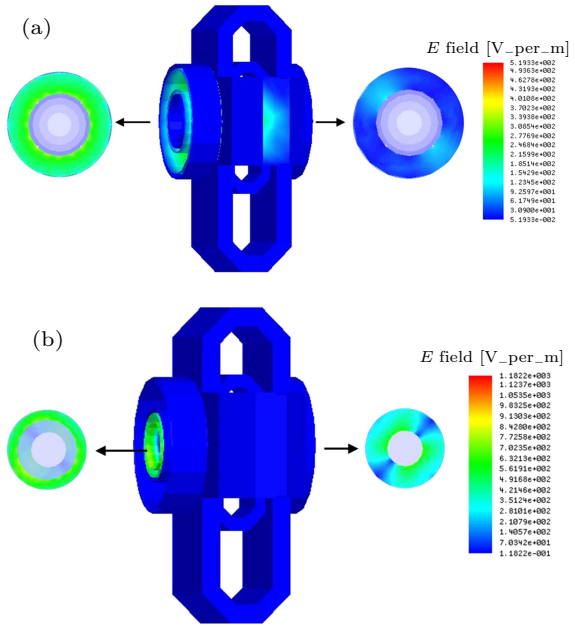


Fig. 3. Electric field distribution at (a) 1.717 GHz and (b) 4.167 GHz in dual-band mode converter.

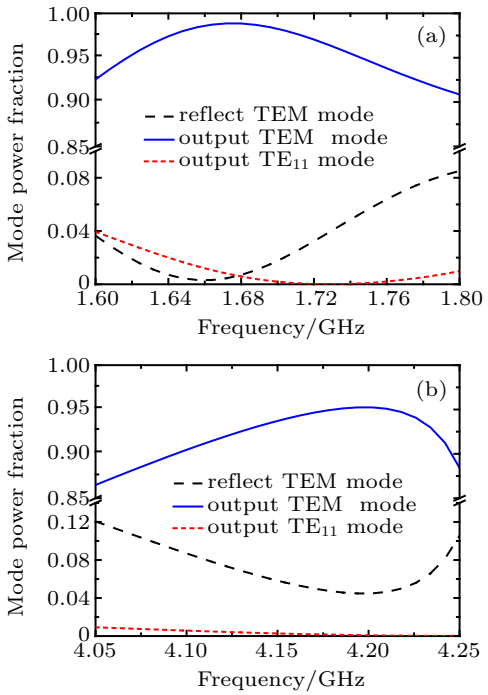


Fig. 4. Mode power fraction of mode converter at (a) 1.717 GHz and (b) 4.167 GHz.

3.2. Dual-band radiation system

The dual-band coaxial conical horn is added to the output port of the dual-band mode converter, and then the whole structure of the dual-band radiation system can be obtained. In simulation, the mode converter and the conical horn can generate the TEM mode reflection, and the circular platform structure that is marked in Fig. 2 in the input port can also generate the TEM mode reflection, as long as the phases of the TEM modes produced by them are opposite but the amplitudes are the same, the reflection can be counteracted by each other.

The whole structure is established and simulated by CST STUDIO SUITE. The injected power is fixed at 1.0 W, and the injected modes are all TEM modes in the simulation at 1.717 GHz and 4.167 GHz. The simulation results are shown in Figs. 5 and 6.

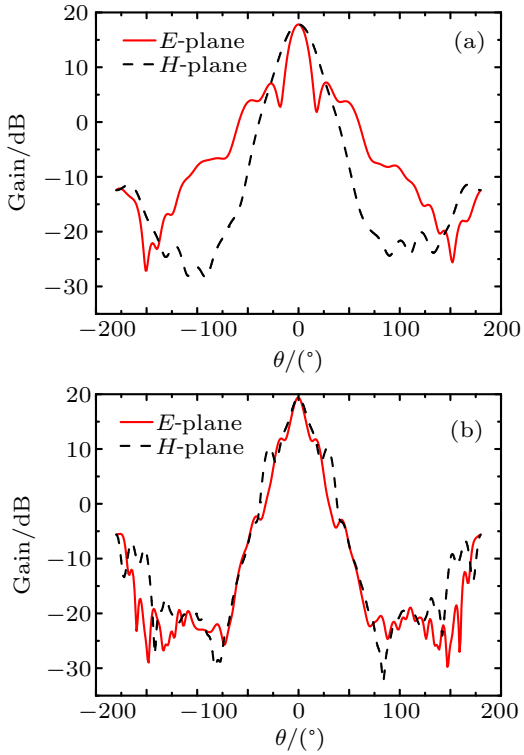


Fig. 5. Radiation patterns at (a) 1.717 GHz and (b) 4.167 GHz of dual-band radiation system.

At 1.717 GHz, the gain of the antenna is 17.9 dB, and the 3 dB beam width is 16.0° in the *E*-plane, and 26.0° in the *H*-plane separately. In the *E*-plane, the first side lobe appears at 27°, and its gain is 7.0 dB. The total return loss of the antenna is 1.50%. The 1.717-GHz microwave can transmit in the inner conical horn, but it is cut off in the C-band's input coaxial waveguide (The inner and outer radius of the C-band's input coaxial waveguide are 34 mm and 45 mm, respectively. The corresponding cut-off wavelength of TE_{11} mode microwave is 102 mm, which is less than the wavelength (175 mm) at 1.717 GHz). So, the diffraction loss is nearly 0.

At 4.167 GHz, the gain of the antenna is 19.4 dB and the 3 dB beam width is 12.0° in the E-plane and 15.1° in H-plane separately. The total return loss of the antenna is 1.17%, and the diffraction loss is only 0.78%.

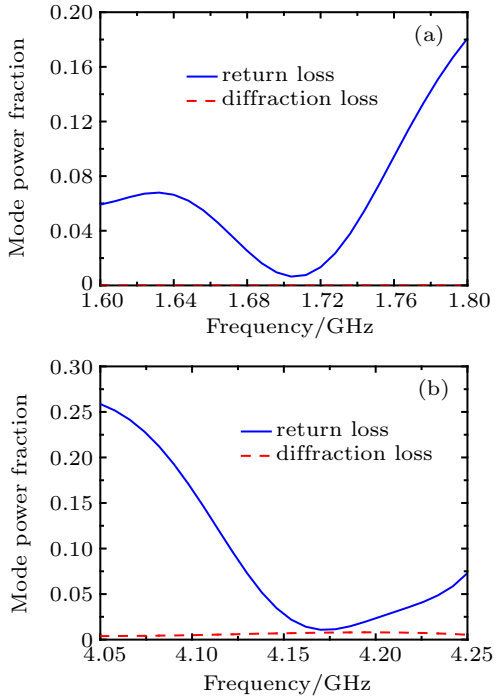


Fig. 6. Rreturn loss and diffraction loss at (a) 1.717 GHz and (b) 4.167 GHz of dual-band radiation system.

The injected power is 1.0 W in simulation. The electric fields of the E-plane in the dual-band radiation system are shown in Fig. 8. The E-plane lies in the direction of the intersection of the two long sides and the intersection of the two short sides of the cross-shaped mode converter as shown in Fig. 7. So the middle part is broken in Fig. 8. The microwave is a quasi-plane wave in the polymer window (Fig. 6(a)). The maximum electric field in the dual-band radiation system is 0.46 kV/m (1.717 GHz) and 1.23 kV/m (4.167 GHz), separately. The HPM systems usually work in vacuum ($\sim 10^{-3}$ Pa), where the breakdown threshold of metal surface is greater than 0.7 MV/cm in short pulse duration (the most modern HPM durations are less than 100 ns). Therefore, the power capacity of the dual-band mode conversion antenna is 23.0 GW at 1.717 GHz and 3.2 GW at 4.167 GHz, separately.[20] But considering the breakdown of the polymer window, the field strength near the polymer window is 84 V/m at 1.717 GHz and 135 V/cm at 4.167 GHz separately, and the breakdown threshold of the polymer window is about 60 kV/cm, the power capacity of the dual-band mode conversion antenna is 5.1 GW at 1.717 GHz and 2.0 GW at 4.167 GHz separately. Therefore, the overall power capacity of the dual-band radiation system is 5.1 GW at 1.717 GHz and 2.0 GW at 4.167 GHz separately. They can basically meet the radiation requirements of dual-band MILO.

The axial length of the original dual-band radiation system is 997 mm.[17] However, the axial length of the compact dual-band radiation system is only 546 mm. Therefore, the axial length is reduced by 45.2%.

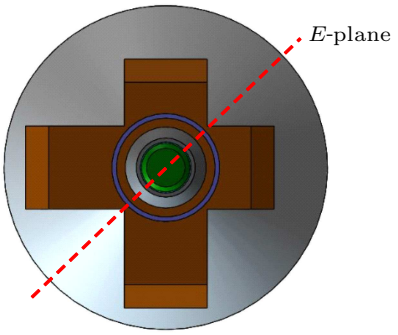


Fig. 7. Schematic diagram of E-plane position of the dual-band radiation system.

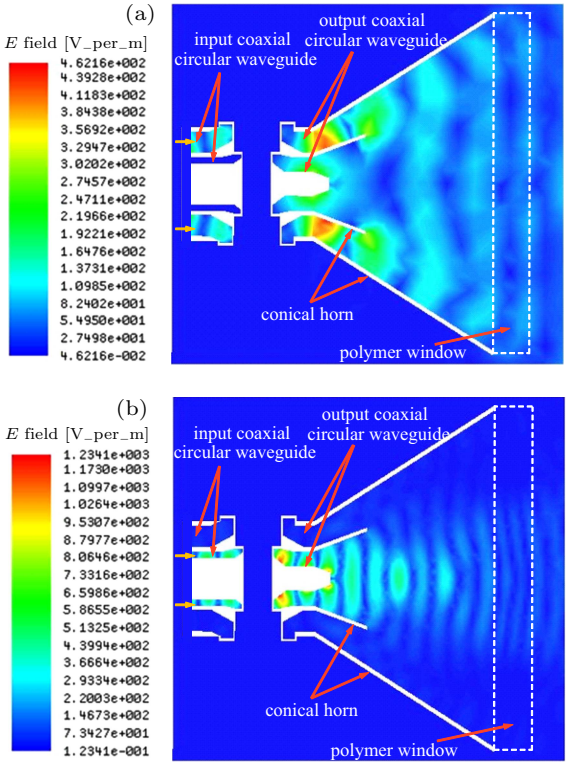


Fig. 8. Electric field at (a) 1.717 GHz and (b) 4.167 GHz of E-plane in dual-band radiation system.

4. Conclusions

In this paper, we presented a compact dual-band radiation system for a complex MILO, which comprises a dual-band cross-shaped mode converter and a dual-band coaxial conical horn. The compact dual-band radiation system can radiate the dual-band TEM mode microwave generated by the complex MILO efficiently. It has a high transmission efficiency, low return loss and high power-handling capacity, which can satisfy the requirements for practical applications of complex MILO. Comparing with the original structure, the length of the dual-band radiation system is reduced by 45.2%. It can also be

applied to other dual-band microwave sources through reasonable improvement.

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