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Study on dispersion characteristics of terahertz waves in helical waveguides

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Corresponding to the atmospheric transmission windows of the electromagnetic spectrum in the low terahertz range, the mode coupling and dispersion characteristics of two helically corrugated waveguides (HCW) in the frequency ranges of 90 GHz–100 GHz and 260 GHz–265 GHz are studied. Through analytic calculations and numerical simulations, dispersion curves and structural parameters of the two frequency ranges waveguides are obtained. A novel method was proposed to obtain the dispersion of the HCW from the eigenwave solution using a periodic boundary condition. The HCW in a frequency range of 90 GHz–100 GHz was fabricated and its dispersion performance was measured. By comparing the measured results with the theoretical and the simulated results, the validity of the analytical and simulation method is verified. Limited to our machining capability, the dispersion of the 260 GHz–265 GHz HCW was only simulated and calculated and it was found that the results agree well with each other.

Keywords: coupling coefficient, dispersion curves, gyrotron traveling wave tube (gyro-TWT), helical waveguide

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1. Introduction

In view of the special position of the terahertz wave (0.1 THz–10 THz) in the electromagnetic spectrum, the electromagnetic wave of this band has both advantages of infrared and microwave. So that it has a broad application prospect in basic research, biomedicine, safety monitoring, and other fields.[1–3] With the rapid development of ultrafast laser technology in recent years, ultra-wideband terahertz pulse sources have been developed rapidly.[4,5] With the development of frequency doubling technology, the high frequency electromagnetic wave output by microwave frequency doubling gradually enters into terahertz frequency band.[6] Unfortunately, many potential applications of this frequency band cannot be put into production practice due to the long-term lack of high-power terahertz radiation sources. It is a world-class problem to generate high enough terahertz wave radiation power, and the realization of terahertz power amplification is a blank field until now. Therefore, to meet the needs of terahertz applications, the development of high-power terahertz radiation source is particularly important and urgent.

It is well known that gyro-TWT (gyrotron traveling wave tube) has many advantages such as high output frequency, high power, and wide working bandwidth. However, the wavelength of terahertz wave becomes shorter with the increase of the operating frequency which leads to smaller cross-sectional size of the device as well as smaller manufacturing tolerances. In order to reduce the difficulty of manufacture and obtain a certain working bandwidth, scientists studied a variety of special-shaped waveguide structure. In University of California, the research group could selectively suppress the parasitic pattern of the angular direction by using the chamfered waveguide.[7] In 1998, a research team composed of Russian and British scholars proposed that helically corrugated waveguide (HCW) could show asymmetric irregular periodicity in the transmission direction. This special structure made the broadband operation possible.[8] Dr. He and his colleagues in the University of Strathclyde have continuously studied on the HCW in W-band, and extended it towards the terahertz region recently.[9–12] Other scientists also studied the mode coupling mechanism and dispersion equation of the HCW.[13–15] In general, the current research in this field is mainly focused on microwave and millimeter wave band.[16,17]

The design of HCW is one of the key technologies in the development of the HCW based terahertz wave amplifier. In this paper, the dispersion performance of HCW which is the core component of terahertz wave amplifier has been studied through theoretical analysis, numerical simulation, engineering realization and finally measurement of the dispersion of the HCW operating in the low terahertz range. Comparing with the other method which is based on the simulation of the wave propagation in the whole waveguide of about 10–20 periods, This paper presents a novel method, by solving eigenwaves in only 1 period, to obtain the dispersion curve of the HCW. This method by using eigenwave solver can save the

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computing time greatly. The dispersion of frequency bands of 90 GHz–100 GHz and 260 GHz–265 GHz were simulated by this method. The HCW dispersion curve for 90 GHz–100 GHz has been manufactured and its dispersion was measured. In this paper, the calculation theory and the parameters selected are given in Section 2. Numerical simulation results of HCWs dispersion in both 90 GHz–100 GHz and 260 GHz–265 GHz are presented in Section 3. The experimental process and results for 90 GHz–100 GHz HCW are shown in Section 4. The research process and feasibility of terahertz amplifier using the HCW are summarized in Section 5 finally.

2. Analytical calculation

As is known to all, every waveguide has its own dispersion property. In circular waveguide dispersion curve is a parabola, and the dispersion curve of electron beam is a straight line described by the formula $\omega = k_z v_z + s\omega_{ce}$. Here ω is the operating angular frequency. k_z and v_z are the axial components of the wave vector and velocity of electron beam respectively. s is the cyclotron harmonic number and ω_{ce} is the relativistic electron cyclotron frequency. Obviously there is only one intersection point between the electron beam dispersion line and the waveguide dispersion curve, which means only around this one point (or frequency) where energy transfer between the beam and wave could happen. The slope of the dispersion curve of the electron beam could be changed by adjusting the amplitude of v_z in the formula. Fortunately an HCW could produce a dispersion curve that has an invariant group velocity over a large frequency band near $k_z = 0$ range. Matching of the ideal dispersion curve to the electron beam dispersion line could achieve efficient beam–wave interaction in a larger frequency bandwidth. The ideal dispersion curve can be obtained by choosing suitable dimensions of the HCW. In the cylindrical coordinate system the radius of the HCW could be described by the following:

$$r(\varphi, z) = r_0 + l\cos\left(\bar{m}\varphi - \bar{h}z\right), \tag{1}$$

where r_0 is the average radius of the waveguide, l is the amplitude of the corrugation, $\bar{m}$ is the number of angular changes of the waveguide, $\bar{h} = 2\pi/d$ is the axial number of the waveguide, and d is the period of an HCW. As described in Refs. [10,18], the threefold helical waveguide structure can provide effective resonant coupling between two partial rotating waves of the waveguide which are the near-cutoff mode A and a far-from-cutoff traveling wave B when the Bragg resonance conditions $\bar{m} = m_A + m_B$, $\bar{h} \approx h_B$ are met. Here, m_A and m_B are the azimuthal numbers of the waves. If the amplitude of the corrugation is small compared with the wavelength, the dispersion equation of the eigenwaves of the HCW can be derived as in Refs. [10,19,20].

$$(h^2 - 2\delta)(h + \Delta_g - \delta/h_0) = 2\sigma^2/h_0. \tag{2}$$

Here variables h, δ, and parameters of Δ_g, h_0, and σ are normalized to k_0. Equation (2) is a cubic equation of the propagation constant of the coupled wave and has three roots, which respectively represent the propagation characteristics of the three eigen-modes in the HCW. Among them one eigenwave has an attractive characteristics for gyrotron travelling wave tubes (gyro-TWT) amplifier with a near constant negative group velocity in the designed operating frequency range.

In this paper, for 90 GHz–100 GHz HCW, the following parameters were selected for numerical calculation of the dispersion equation (2). The average radius of the helical waveguide was 1.45 mm. The corrugation amplitude was 0.22 mm and the periodicity length was 3 mm. The dispersion characteristic curve of the HCW can be obtained by numerical calculation, as shown in Fig. 1.

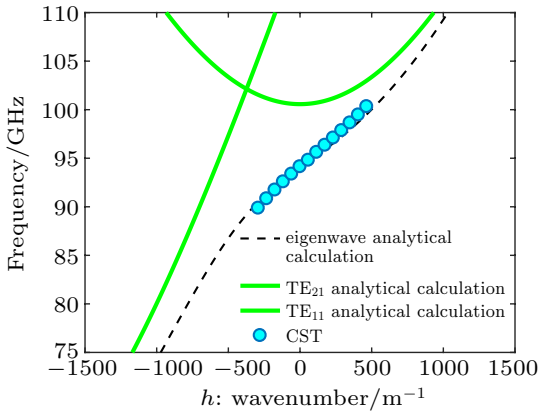


Fig. 1. Dispersion of the 90 GHz–100 GHz HCW, the black curve is theoretically calculated result, the light blue circle is the simulation result using CST Microwave Studio.

In Fig. 1, the green solid lines (TE_{11} and TE_{21}) respectively represent the dispersion curves of the two partial rotating waves of the waveguide and the black dashed line represents the dispersion curve from the resonant coupling of these two modes. It was found that the dispersion curve of the HCW tends to be a positive slope of the straight line and the group velocity of the wave is about a constant.

3. Numerical simulation and analysis

The dispersion characteristics of HCWs with different corrugation period and period are numerically calculated. It is found that with the increase of corrugation amplitude, the linearity of the coupled wave becomes better. This characteristic is beneficial to broaden the frequency band of the gyro-TWT. The influence of the change of the period on the dispersion characteristics of the HCW is as follows: when the period is small, the linear variation of the coupling wave becomes worse and the linear region becomes very narrow. The width of the linear region determines the bandwidth of the beam–wave interaction, so the selection of the period is very important for the beam–wave interaction of the gyro-TWT.

In previous published papers,[10,21,22] an HCW of at least 10-period was modelled to calculate the dispersion characteristics. This method tends to be time consuming by considering the long structure of the whole corrugated waveguide and the large number of grids. By utilizing the periodic boundary condition and setting the phase shift of the wave in the period, any wave modes satisfying the conditions could be identified by an eigenwave solver, therefore the results could be used to calculate the dispersion of any mode within the helical period. This eigenwave method could improve the calculation accuracy and reduce the calculation time. In this paper, eigenwave mode solver from the CST Microwave Studio is used to solve any modes that satisfy the conditions and gives out the corresponding mode frequency and axial wave number of the mode.

An eigenmode of waveguide is a pattern of free motion in which all parts of the waveguide move sinusoidally with the same frequency and with a fixed phase relation. The free motion described by the eigenmodes takes place at its fixed natural frequencies or resonant frequencies. Eigenmodes depend on waveguide's structure, material, and boundary conditions. In CST, the eigenmode solver is used to calculate the frequencies and the corresponding electromagnetic field patterns of eigenmodes when no excitation is applied.

In our eigenwave mode simulation in one period of HCW with threefold HCW structure and pure copper material, all boundaries were electric ($E_t = 0$) except the propagation direction of electromagnetic wave which was periodic, and the Advanced Krylov Subspace (AKS) method was used to calculate all 14375 hexahedral cells only using 35-second calculation time including 11-second mesh generation time, and 24-second solver time. From the front face to back face of one period waveguide, the phase shift θ were set as -90° to 90° and 10 modes of electromagnetic wave were calculated every 10°.

At 0° the good pattern of electric field has been shown in Fig. 2. At any degree we could find the coupling electromagnetic mode always rotating clockwise or counterclockwise along the direction of propagations.

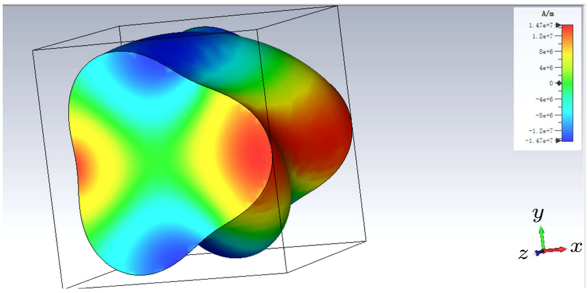


Fig. 2. Electric field pattern of the coupling electromagnetic mode.

Through pattern recognition, the phase shifts in the range of -50° to 80°, with a step of 10°, were selected and recorded. Transmitting the periodicity length of $d = 3$ mm, all modes of axial wave numbers for electromagnetic waves could be obtained by $\bar{h} \times \theta/360$. With the corresponding frequencies of the coupling mode, the dispersion curve could be obtained which was shown by the light blue circle in Fig. 1. It can be found that simulation result matched well with theoretical result in the frequency band of 90 GHz–100 GHz, which can tell us that the dispersion curve of HCW in this frequency band is a straight line with a positive slope.

In order to verify the applicability of the HCW in terahertz high frequency band, the dispersion equation (2) was used to design an HCW operating at 260 GHz–265 GHz band. The average radius of the HCW was selected to be 0.54 mm. The corrugation amplitude was designed as 0.05 mm and the helical cycle length was 1.22 mm. The dispersion characteristic curve of the HCW can be obtained by numerical calculations of the dispersion equation, as shown in Fig. 3. It can be seen that the HCW dispersion curve is still a straight line with a positive slope within the 5-GHz bandwidth and the simulation results are in good agreement with the theoretical calculation results, thus proving the feasibility of the method to expand to higher frequency terahertz waves.

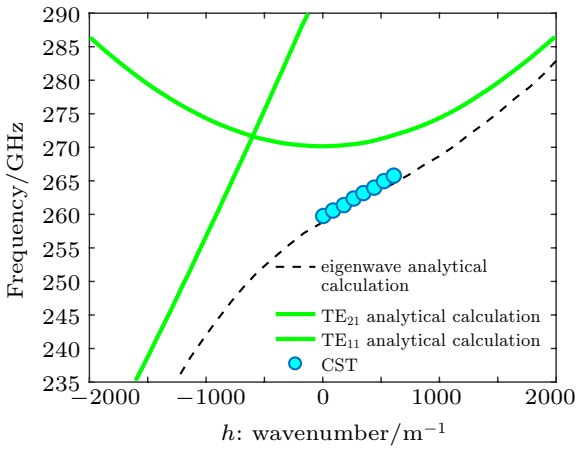


Fig. 3. Dispersion of the 260 GHz–265 GHz HCW, the black curve is theoretically calculated result, and the light blue circle is the simulated result using CST Microwave Studio.

4. Experimental measurement and analysis

HCWs of 90 GHz–100 GHz were manufactured as shown in Fig. 4. The dimensions of the HCW were too small to be produced by normal manufacturing process. Electroforming technology had been adopted. Firstly, an aluminum mandrel was manufactured by machining. Secondly, by electroplating oxygen free copper on the outer surface of the mandrel to compose waveguide wall and then mandrel was etched away chemically in order to obtain special shaped waveguide.



Fig. 4. A picture of 90 GHz–100 GHz HCW.

HCW transmission frequency response for 90 GHz–100 GHz had been tested using the vector network analyzer of the 75 GHz–110 GHz test platform. The experimental setup consisted of a HCW and a vector network analyzer, a pair of rectangular waveguides, a pair of rectangular circular waveguides, a pair of circular polarizers and a pair of transmitting and receiving modules, as shown in Fig. 5. For the convenience of manufacture, each circular polarizer was composed of two parts.

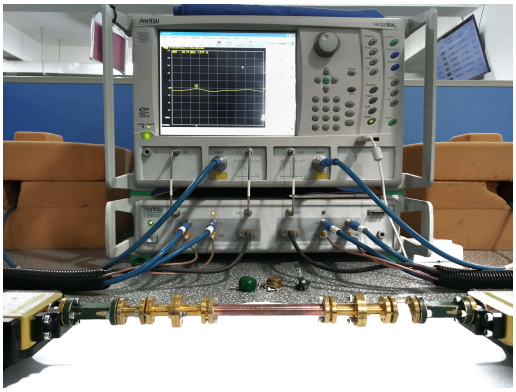


Fig. 5. Experimental setup of dispersion characteristics of 90 GHz–100 GHz HCW.

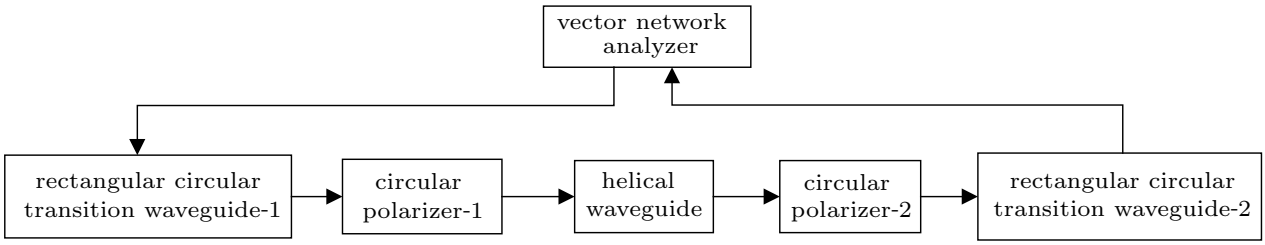


Fig. 6. Schematic diagram of the setup used in the dispersion measurement.

As shown in Fig. 6, the circular polarizer 1, HCW and circular polarizer 2 were connected. The axial direction of the circular polarizers 1 and 2 was along the z axis in the coordinate system of Fig. 7, which was the direction of electromagnetic wave propagation. The circular polarizer was used to change the polarization of the wave from the linear to circular and *vice versa*. In the setup the long axes of the two polarizers were placed perpendicular to each other, which were set at angles of either 45° or 135° with respect to the polarization of the linear wave respectively. The electromagnetic wave was transmitted from circular polarizer 1 to circular polarizer 2 in the two setups, in which the right-handed circular polarized wave is generated in Fig. 7(a) and left-handed in Fig. 7(b). Consequentially, one of the rotation relations is the same as the rotation direction of the corrugation inside the HCW. Because HCW is opaque, the phase evolutions with and without the HCW were measured respectively in the case of these two rotation relations. The propagation characteristics of the HCW device could be obtained by subtracting the phases without the HCW from the phase when the HCW was connected. The phase evolution due to the HCW was then converted into k_z value by $k_z = \varphi/L$, and then the dispersion of the HCW could be obtained as shown with the blue curve in Fig. 8. The small deviation between the experimental value and the theoretical or simulation value mainly comes from the machining error of the HCW and measurement error.

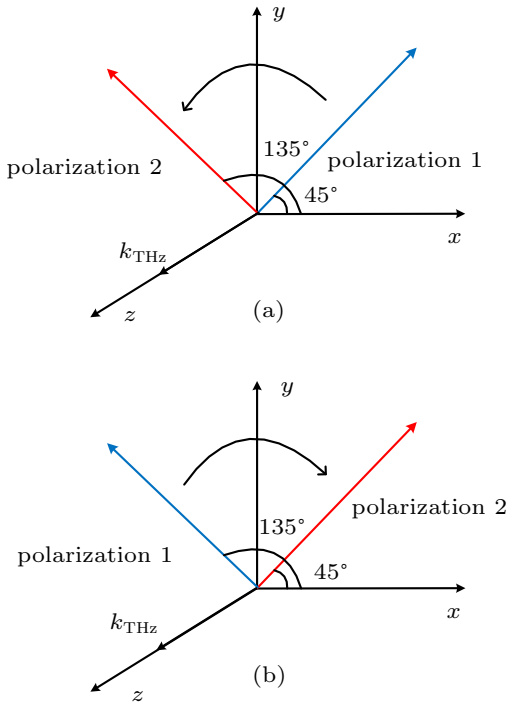


Fig. 7. Schematic diagram of short axis position of the circular polarizers to produce (a) the right-handed circular wave and (b) the left-handed circular wave.

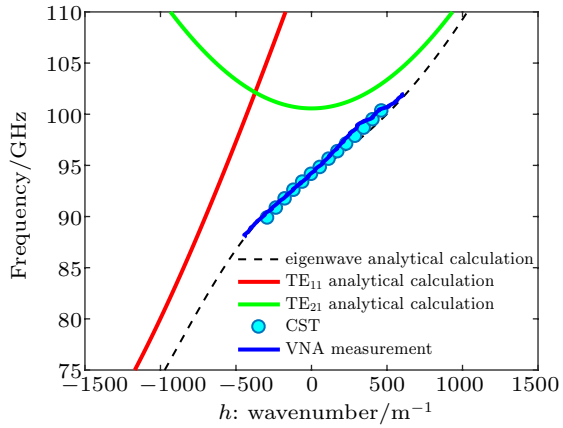


Fig. 8. Dispersion curves of the 90 GHz–100 GHz HCW. The black curve is the calculated value, the light blue circle is from the simulation, and the blue curve is from the Vector Network Analyzer measurement.

5. Conclusion

Based on the coupled wave theory, the cold cavity dispersion equation and mode coupling condition of HCW are used to obtain the dispersion characteristics of interaction zone between terahertz wave and electron beam in gyro-TWT. At the same time, from the numerical simulation, the dispersion curves of the HCW were obtained at the frequencies of 90 GHz–100 GHz and 260 GHz–265 GHz respectively, which agree well with theoretical calculation results. To further verify the correctness of the numerical simulation and theoretical calculation, the HCW working in 90 GHz–100 GHz band had been fabricated by electroforming process and cold test experiment was carried out. Comparing experimental test results with the numerical simulation and theoretical calculation of dispersion curves, we find they match each other very well so as to demonstrate the validity of theoretical calculation and simulation. The research in this paper can verify the feasibility of terahertz wave power amplifier with a certain bandwidth using the HCW.

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