A Novel Ridge-Gap-Waveguide Slow-Wave Structure for G-Band Travelling-Wave Tube

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***Abstract*— In this paper, a novel grating ridge-gap-waveguide (RGW) slow wave structure (SWS) for G-band travelling wave tube is presented. Ease of fabrication, because of no need to metal contact between the upper and lower plates, is one of the most important advantages of this kind of SWS. In addition, this structure has the potential to have higher interaction impedance than the conventional grating amplifiers, due to more uniform axial electric field distribution over the sheet beam cross section. Moreover, the most of higher harmonic modes and backward waves, within the stop band of the RGW, can be considerably suppressed. The high frequency characteristics of the proposed SWS, such as phase velocity and interaction impedance, are calculated by the help of CST software. Furthermore, the PIC simulation has been performed by using CST particle studio to predict the interaction between sheet beam and electromagnetic waves. Our study shows that the proposed TWT can generate the peak power of 149W at 220 GHz, corresponding to the maximum gain and efficiency of 41.7dB and 2.6%, respectively.**

***Index Terms*—G-band, grating amplifier, ridge gap waveguide (RGW), slow wave structure (SWS), travelling wave tube (TWT).**

I. Introduction

TRAVELLING wave tubes (TWTs) offer significant potential for compact high power amplifiers with relatively high efficiency and high bandwidth in the millimeter- wave and terahertz (THz) regimes. They can be used for applications such as high data-rate communications, medicine, biology, advanced electronic materials spectroscopy, space research and remote sensing [1]. The key component of each TWT is the slow wave structure (SWS) which determines the main characteristics of the tube. The practical feasibility for fabrication of SWSs, especially at high frequencies, has long been a major challenge for the designer. Accordingly, many studies have been conducted so far to design the different types of SWSs which have more suitable performance as well as advantage of easy fabrication. Some of the most popular SWSs presented for high frequency

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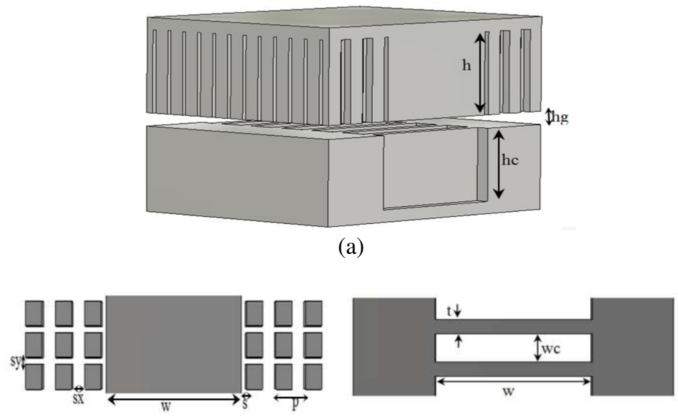


Fig. 1. (a) Novel grating ridge-gap-waveguide (RGW) slow wave structure, (b) top plate view and (c) bottom plate view.

TWTs are folded waveguides [2], [3], grating waveguides [4], [5], microstrip meander-lines [6] and planar helical structures with straight-edge connections [7]. Among these structures, the grating waveguide is an attractive choice because of high power handling capacity, low losses and relatively easy fabrication. However, the grating waveguide requires electrically conducting sidewalls, therefore, it must be manufactured in two blocks that need to be joined with high precision without any air gap between metal walls. So, the fabrication of this type of SWS has some serious difficulties, especially at high frequencies. In order to overcome this drawback and improve some characteristics of the conventional grating amplifiers, we propose a novel grating slow wave structure based on ridge gap waveguide (RGW) concept [8], [9]. Ease of fabrication is the first advantage of this novel structure. The main reason of this advantage is that in the ridge gap waveguides no metal contact is required between the upper and lower plates of the grating waveguide near the interaction region. In other words, the bed of nails creates a high impedance surface (HIS), over a certain frequency range. With the metallic top plate, it forms a PEC-HIS parallel plate waveguide which exhibits an electromagnetic band-gap which prevents the fields from leaking transverse to the propagation direction [9]. Therefore, the connection between the upper and lower plates of the SWS can be implemented with considering only mechanical considerations. Second, since the basic mode of the novel proposed structure is a quasi-TEM mode, the axial electric field distribution over the sheet beam cross section is relatively uniform. Consequently, this type of SWS has

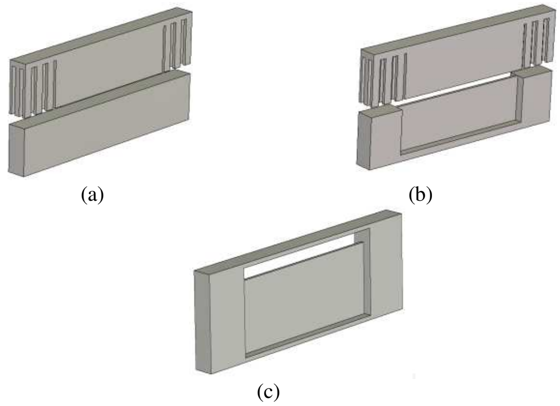


Fig. 2. The basic cells of, (a) the conventional RGW, (b) the novel grating RGW SWS, (c) the conventional grating SWS.

potential to have higher interaction impedance than the conventional grating amplifiers. Third advantage is that the novel proposed SWS has a reduced higher order mode and backward waves content, because these modes cannot be confined at frequencies outside of the PEC-HIS band gap. Therefore, the required amount of the sever attenuation is reduced which leads to increasing the gain and decreasing the losses.

The present paper will describe the design and characteristics of the novel grating RGW SWS for G-band travelling wave tubes. The design description and electromagnetic properties, such as dispersion diagram, interaction impedance and scattering parameters are investigated in Section II. The PIC simulation results are presented in section III, followed by the conclusion in Section IV.

II. DESIGN DESCRIPTION AND ELECTROMAGNETIC PROPERTIES

Fig.1 shows the novel grating RGW slow wave structure in which the groove grating has been placed over the ridge with the same width. To confine the excited wave only along the ridge, the bed of nails should create a high impedance condition over desired frequency band when the gap distance is smaller than a quarter- wavelength [9]. Therefore, the height of the nails (h) should be near a quarter- wavelength. In addition, when the h_g is so small, the grating region and the conducting ridge above it form a PEC-HIS parallel plate waveguide which exhibit an additional electromagnetic band-gap. This electromagnetic band-gap should be far enough from the operating frequency. So, the grating depth should be smaller than a quarter- wavelength. Accordingly, the dimensional parameters of the proposed SWS for G-band TWT application are selected as follows: hg = 0.075mm, h = 0.35mm, hc = 0.27mm, w = 1.1mm, s = 0.02mm, sx = 0.05mm, sy = 0.03mm, p = 0.11mm, t = 0.02mm and wc = 0.12mm. Moreover, the metal material is set as high-conductivity copper with conductivity of 2.25×10^7 S/m [10].

Fig. 2 depicts the basic cells of the conventional RGW, the novel grating RGW SWS and the conventional grating SWS. These simulation models are used in Eigen-mode solver of CST for calculating the electromagnetic properties of the mentioned structures. It should be noted that the common

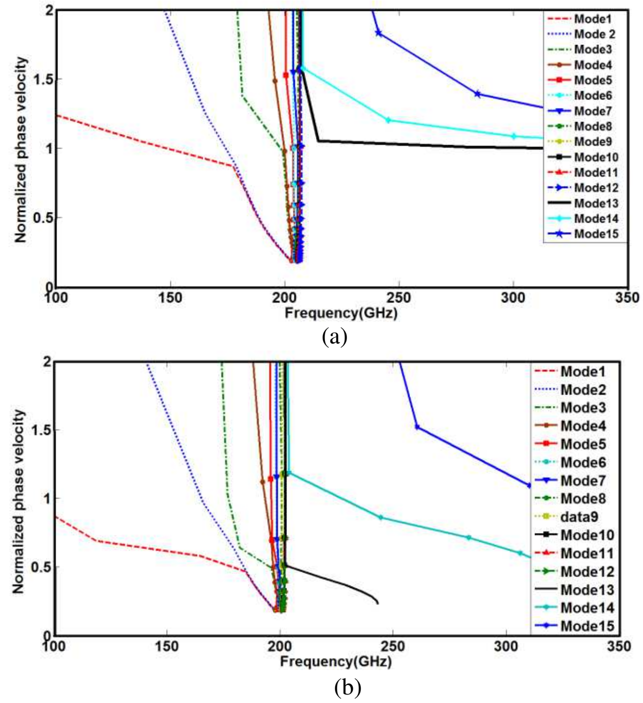


Fig. 3. (a) The normalized phase velocity of the first 15 modes of the conventional RGW (shown in Fig. 2(a)), (b) the normalized phase velocity of the first 15 modes of the novel grating RGW SWS (shown in Fig. 2(b)).

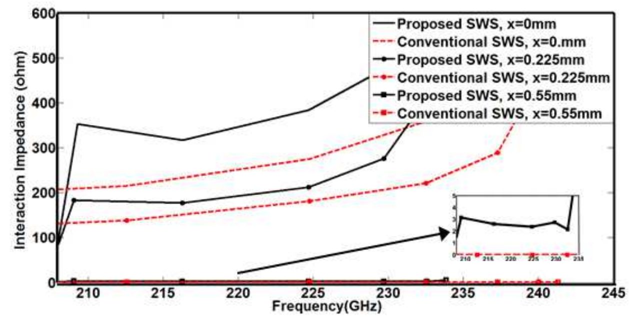


Fig. 4. The interaction impedance of the proposed grating RGW and the two conventional grating SWSs.

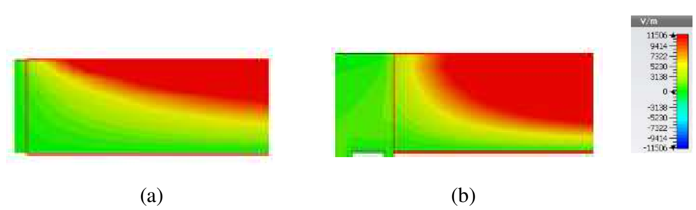


Fig. 5. Axial electric field distribution over the half cross section of, (a) conventional grating SWS and (b) the novel grating RGW SWS.

dimensions of the three structures are the same. Furthermore, to dissipate the waves that are not confined along the ridge, we set the boundary conditions of side walls, in Figures 2(a) and 2(b), as the conducting wall with conductance of 1000 S/m with the distance of 0.01 mm from the side walls. Now, to get a good understanding of different mode types of the novel grating RGW SWS, we first investigate the phase velocity of different modes of the conventional RGW. Fig. 3(a) shows the normalized phase velocity of the first 15 modes of the conventional RGW. According to this figure, several rectangular waveguide type modes appear below 207GHz which is the lower edge of the PEC-HIS stop band. They have a lower cut-off similar to normal rectangular waveguide modes, but go into a stop band slightly below 207GHz [9]. Furthermore, the 13^{th} mode is a quasi-TEM mode with the phase velocity near the velocity of the light within the parallel plate stop band [9]. Consequently, this mode can be confined along the ridge and therefore it can be considered as the desired mode of the novel grating RGW SWS for G band TWT application. Fig. 3(b) illustrates the normalized phase velocity of the novel grating RGW SWS. As expected, by adding the groove grating, the phase velocity of the 13^{th} mode is considerably reduced. As a result, the novel proposed grating RGW has the potential of utilizing as the slow wave structure for G band TWT applications.

Fig. 4 compares the interaction impedance of the proposed grating RGW and the conventional grating SWS, shown in Fig. 2(c), at three different distances from sheet beam axis. It is obvious that the axial electric field on the two vertical conducting sidewalls of the conventional grating SWS should be vanished. So, the axial electric field intensity near these PEC boundaries will be considerably reduced (Fig. 5(a)). On the other hands, the two PEC-HIS parallel plate waveguides on the both sides of the grating RGW prevent the fields from leaking transverse to the propagation. Therefore, the field propagating along the central ridge will experience these two parallel-plate cut-off regions as if they were PMC boundaries [9]. As a result, due to existence of the tangential components of electric field on the PMC boundaries, the axial electric field distribution will be more uniform over the sheet beam cross section (Fig. 5(b)). Consequently, the interaction impedance of the novel grating RGW should be higher than the conventional SWS, as can be seen in Fig. 4.

Fig. 6(a)-(c) show the scattering parameters results for 100 unit cells of the conventional RGW (Fig. 2(a)), conventional grating SWS (Fig. 2(c)) and novel grating RGW (Fig. 2(b)) computed by CST microwave studio. Fig. 6(a) indicates that the RGW has been properly designed to guide only the waves with frequency around 220GHz. According to Fig. 6(b), when the gap distance is smaller than a quarter- wavelength, the grating region and the conducting plate above it form a PEC-HIS parallel plate waveguide which exhibit an additional electromagnetic band-gap from 270GHz to 440GHz. So, we expect that the novel grating RGW SWS shows a wide stop band to considerably reject higher order modes and backward waves. Fig. 6(c) confirms the wide stop band of the novel grating RGW in addition to acceptable transmission characteristics within the desired frequency band.

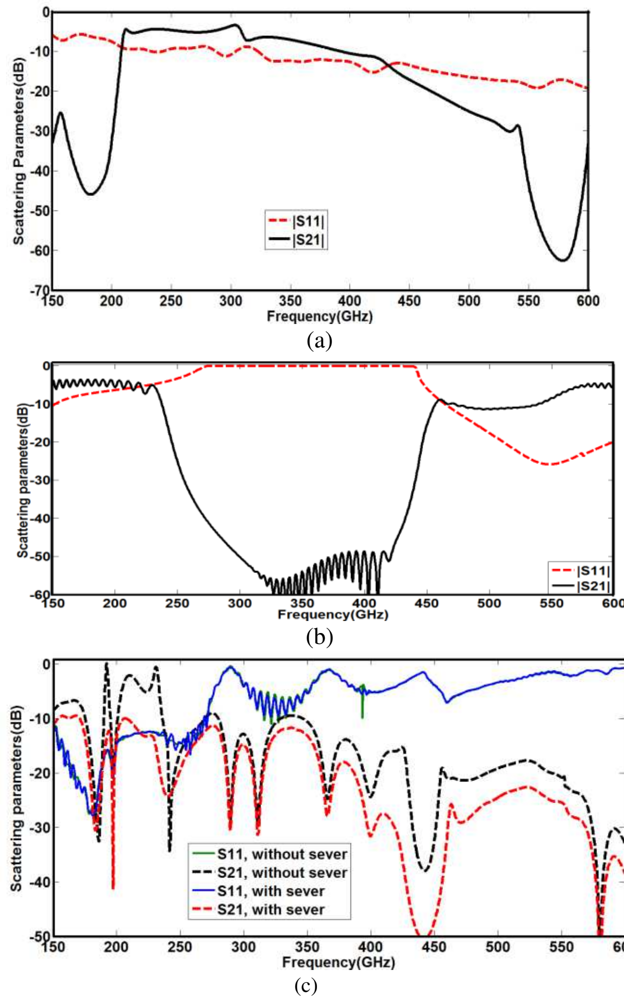


Fig. 6. The scattering parameters results for 100 unit cells of (a) the conventional RGW, (b) the conventional grating SWS and (c) the novel grating RGW with and without sever.

III. BEAM-WAVE INTERACTION SIMULATIONS

In this section, the interaction between the electron sheet beam and the electromagnetic waves in the G-band TWT, with the novel grating RGW as the SWS, is simulated. All of the PIC simulations have been performed by CST particle studio. In the simulation, we assume that the sheet beam has a cross sectional area of 0.11mm × 0.03mm with a voltage of 38 kV and current 150 mA. The distance between the sheet beam and the grating surface is 0.005mm. In addition, a uniform longitudinal magnetic field of 1.7T is used to concentrate the sheet beam and a sinusoidal RF signal with a peak power of 10mW is applied as an input signal into the proposed TWT. The designed TWT is composed of 200 grating RGW unit cells shown in Fig. 2(b). Therefore the overall length of the proposed TWT will be 56mm.

To attenuate reflected waves as well as backward waves, we add some losses to unit cells of 25^{th} to 45^{th} as the sever. As previously mentioned, the novel proposed SWS has a reduced higher order mode and backward waves content, so, the required amount of the added losses expected to be relatively low. This fact has been illustrated in Fig. 6(c) where the scattering parameters of the proposed TWT with and without sever have been compared. This figure indicates that the amount of sever attenuation, in comparison with typical severs, is small. As a result, the temperature rising in the tube, especially at the sever region, should be relatively lower than the conventional tubes. Consequently, the required cooling system for the novel grating RGW TWT may be simpler, lighter and cheaper.

Fig. 7 shows the output signal of the designed TWT in comparison with the input one at operating frequency of 220GHz. According to this figure, the peak power at 220GHz is around 149W which is corresponding to gain of 41.7dB. In addition, Fig. 8(a) indicates the frequency spectrum of the reflection and backward-wave signals. It is apparent that the main spectral lines have been placed at 220GHz (input signal frequency), 440GHz (second harmonic mode frequency) and 537GHz (backward wave signal frequency) which all of them have been considerably attenuated. Meanwhile, Fig. 8(b) verifies the good spectrum quality of the output signal where the main spectral line has placed at 220GHz (the input signal frequency) with an amplitude of more than 800 times the reflected signal amplitude.

Fig.9 illustrates the output power and the gain of the proposed TWT versus frequency. According to this figure, the 3-dB bandwidth of the novel TWT is approximately 5.7GHz, ranging from 216.5GHz to 222.2GHz. We think the extreme dependence of the novel grating RGW dimensions on frequency may lead to such narrow bandwidth.

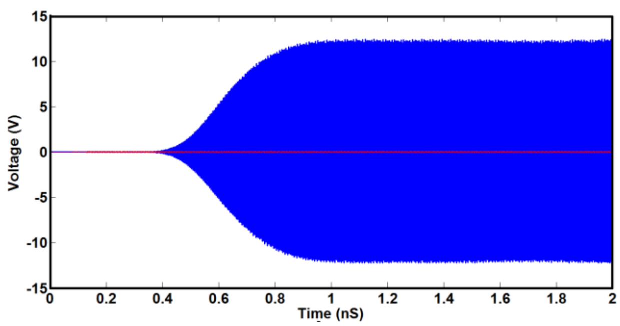
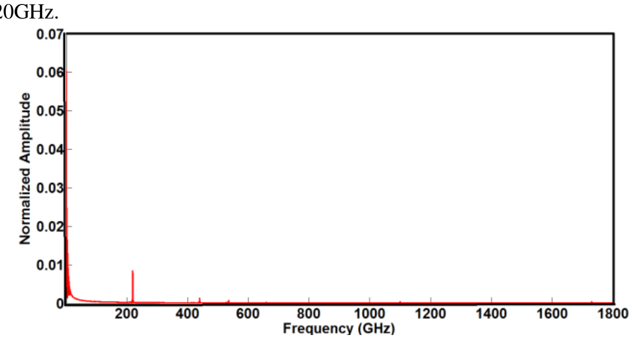
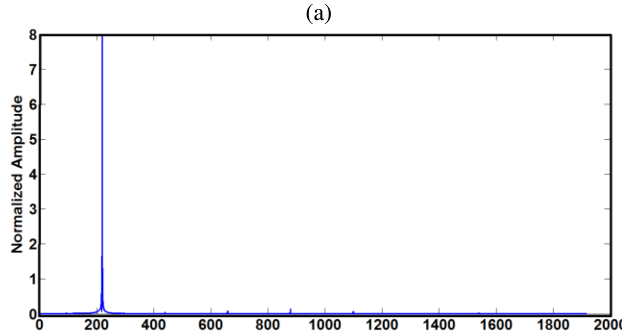


Fig.7. Output signal (blue) in comparison with the input signal (red) at 220GHz.



(a)



(b)

Fig. 8. (a) Frequency spectrum of the backward-wave signal and reflection signal, (b) Frequency spectrum of the output signal.

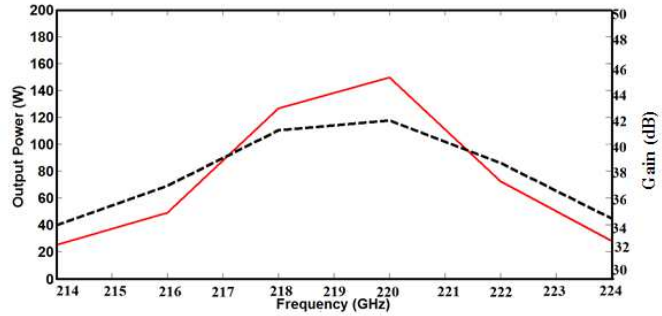


Fig. 9. Output power (solid line) and the gain (dash line) of the proposed TWT.

IV. CONCLUSION

In this paper, the novel grating RGW SWS has been introduced. Phase velocity, interaction impedance and scattering parameters of the proposed SWS have been investigated by means of CST software. According to these simulations, some advantages of the novel SWS, such as high interaction impedance and reduced higher order mode and backward waves content, have been verified. Finally, a G-band TWT with the novel grating RGW SWS has been designed and the interaction between electron sheet beam and the electromagnetic field has been studied using CST-Particle Studio. According to the beam-wave-interaction simulations results, at a design voltage of 38 kV and a current of 150 mA, the proposed TWT can generate the peak power of 149W at 220 GHz, corresponding to the maximum gain and efficiency of 41.7dB and 2.6%, respectively. In addition, the 3-dB bandwidth of the novel TWT is only about 5.7GHz which can be considered as a shortage for this kind of TWT.

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