A Novel Feeback Circuit of Beam-Wave Interaction for THz Amplifier

Luanfeng Gao [1], Yulu Hu [2], Quan Hu [3], Xiaofang Zhu [4], Jianqing Li [5], Bin Li [6], Tao Huang [7], Wenkai Deng [8], Xiaobing Wang [9]

National Key Laboratory of Science and Technology on Vacuum Electronics
Academy of Computer Simulation Technology, University of Electronic Science and Technology of China
NO.4, Section 2, North Jianshe Road, Chengdu, P. R. China 610054
gaoluanfeng@163.com[1], yuluhu@uestc.edu.cn[2], huquan1981@uestc.edu.cn[3], zxf@uestc.edu.cn[4], lijq@uestc.edu.cn[5], libin@uestc.edu.cn[6], huangtao@uestc.edu.cn[7], 1115688480@qq.com[8], 1054658734@qq.com[9]

Abstract: *This paper describes the working and dispersion synchronization condition of the novel beam-wave interaction to develop a watts-level, tunable THz amplifier, which can enhance the gain and reduce the starting current. In the feedback circuit, two beams can be possibly coupled with HOM as their beam position has a strong coupling with the modes. Thus, the HOM is analyzed. Simulation results show that the high order mode excitation cannot become dominant in the feedback circuit.*

Keywords: Terahertz, Beam-wave Interaction, Feedback Circuit, High Order Mode Excitation

Introduction

The forward and backward wave feedback circuit is an innovation of beam-wave interaction circuits for vacuum electron devices. Different from traditional traveling wave tubes (TWTs) and backward wave oscillators (BWOs), it uses two different speed electron beams to interact with two spatial harmonic components (1st and -1st spatial harmonics) at same frequency respectively. Then, the forward wave and backward wave, which are connected by the feedback circuit, promote each other and finally stabilize the output in two directions. Furthermore, the maximum gain of the forward wave of the feedback circuit is higher than the traditional TWT and the excitation of the backward wave is lower than the traditional BWO[1]. In this paper, more details about the working of the feedback circuit are described. Slow wave structure (SWS) is used for the feedback circuit, it can be easily coupled with high order mode(HOM). So, in this paper, the high order mode excitation was discussed.

The Working of Feedback Circuit

The feedback circuit was based on the amplitude changes of the axial electric field, which can depict the power amplification through beam wave interaction[1]. As the electric field is the summation of an infinite number of spatial harmonics, it is necessary to analyze the effects of space harmonics, which transmit in periodic SWS, during the beam-wave interaction. From traditional beam-wave interaction theoretical, the absolute value of group velocity of different orders of space harmonics (v_{gn}) is equal to the absolute value of group velocity of 0th space harmonic (v_{g0}). That is, an infinite number of space harmonics composed of forward wave and backward wave is transmitted to the + Z or -Z direction to form a power flow.

$$v_{gn} = \frac{\partial \omega}{\partial \beta_n} = \left(\frac{\partial \beta_n}{\partial \omega}\right)^{-1} = \pm \left(\frac{\partial(\beta_0 + \frac{2\pi n}{p})}{\partial \omega}\right)^{-1} = \pm \left(\frac{\partial \beta_0}{\partial \omega}\right)^{-1} = \pm v_{g0}$$

Thus, the traditional slow wave circuit is a two-way transfer without an electron beam, the electromagnetic field in the slow wave circuit is transmitted at the input and output port. According to the beam-wave theory, the principle of the feedback is based on that the power amplification through beam wave interaction is wholly depicted by the electric field amplitude. So, the feedback circuit is formed (shown in Fig. 1), where the forward wave and backward wave will be amplified and promote each other. Meanwhile, they are travel in direction of the beam and the opposite direction of the beam, respectively.

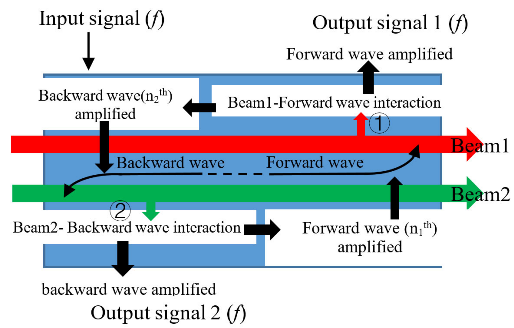


Fig. 1 the forming of the feedback circuit

Slow wave structure is the most important part for TWT and BWO, plays a decisive role in the performance of microwave devices. The dispersion characteristic is the main parameters of SWS and related to the working voltage, frequency bandwidth, working frequency, and working stability of microwave tubes. In order to establish the feedback circuit of beam-wave interaction, an appropriate SWS is required. The SWS is considered available if either of the following synchronization condition of dispersion is satisfied. When the fundamental wave of the Brillouin dispersion curve is a forward wave, the relationship between the dispersion curve and the voltage line must meet the dispersion relationship shown in Fig. 2(a). While, the fundamental wave a backward wave, it should meet the curve in Fig. 2(b).

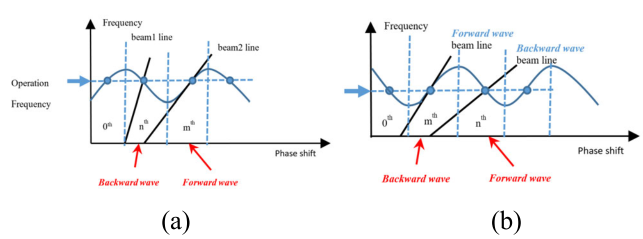


Fig. 2 the sketch of the synchronization condition.

High Order Mode Excitation

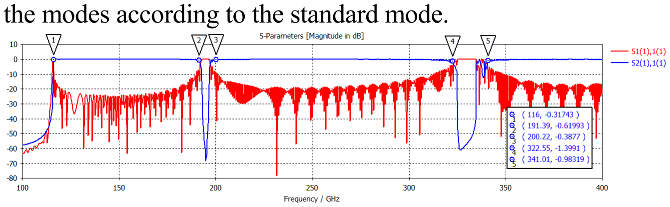
Two beams can be possibly coupled with HOM as their beam position has a strong coupling with the modes. Thus, the HOM is analyzed in this section.

Due to the existing of the electron beam tunnel, it will break the boundary condition at the center section of SWS, which will lead the electric distribution to the hybrid mode. While the

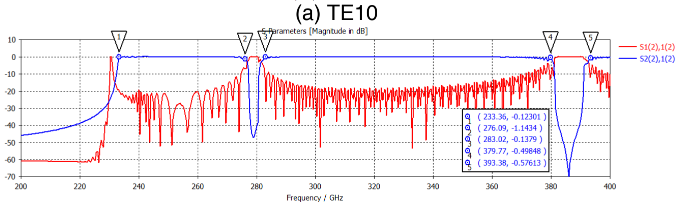
978-1-5386-8288-3/20/$31.00 ©2020 IEEE

electric distribution at the port of SWS is still the standard mode (TE10, TE20, TE11 and so on). Thus, we should focus on the electric distribution of port mode, and the HOMs of FWG SWSs are typically labeled in the standard mode of a standard rectangular waveguide. According to the transverse electric field distribution of various mode at the port, it can be seen that TE10 mode contains the mode1,3,6 of the dispersion curves. The TE20 mode contains the mode 2,4,8. While the TE30 contains the mode5,7.

To verify this conclusion, the scattering matrix graphs of the interaction circuit of TE10 and TE20 were conducted. The S-parameter of TE10 and TE20 have been shown in Fig. 3. The dispersion curve of TE10 and TE20 is shown in Fig. 4. It can be see that the passband and forbidden band of SWS and interaction structure remain the same, so it is possible to divide the modes according to the standard mode.

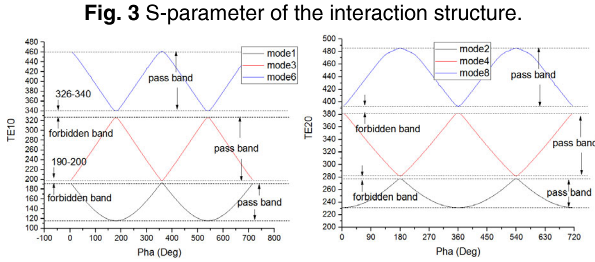


(a) TE10



(b)TE20

Fig. 3 S-parameter of the interaction structure.

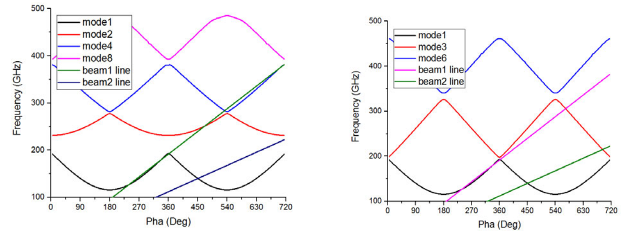


(a) TE10 (b) TE20

Fig. 4 The dispersion curves with passband and forbidden band.

Thus, the first HOM is the TE20, which contains the propagation modes 2, 4, 8. Two beams can be possibly coupled with higher order modes of TE20. Fig. 5 shows the beam1 line is close to the forward wave region of TE20 mode curves. It seems two of them could interact with each other. While, due to the beam-wave interaction theory, the electron beams only have the possibility to interact with the backward wave of TE20 instead of forward wave. Fig. 5 (b) shows the beam1 line and beam2 intersects mode 3 in the region of the -2nd spatial harmonics. There are two frequency points, which in the region of the backward wave, maybe may oscillate later in time. While, we computed the interaction impedance of mode1, mode2 and mode3 in the beam tunnel (shown in Fig. 6). The interaction impedance of TE20 is larger than TE10. So the point located in mode3 is most likely to be excited.

While, the interaction impedance of the two frequency points in mode 3 are 5.036e-4 Ω and 2.318e-5 Ω , which are too small to be excited. Thus, the two points may not oscillate.



(a) (b)

Fig. 5 The dispersion curve of TE10 and TE20 with beam1 and beam2.

To have a deeper understanding of this interaction procedure accurately, a set of longer time simulations is conducted. According to the output signal and the frequency spectrum(shown in Fig. 7), the output signals are stable even at 50 ns. Thus, combining the analysis of the time-transient and the frequency domain, the HOM excitation could not become dominant and did not appear in the feedback circuit later in time during simulation.

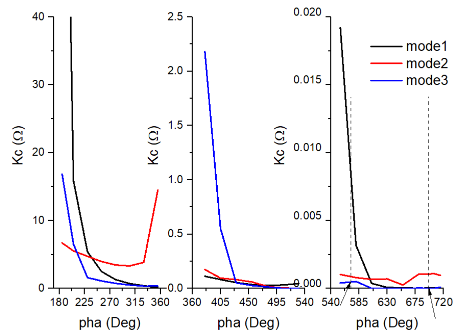
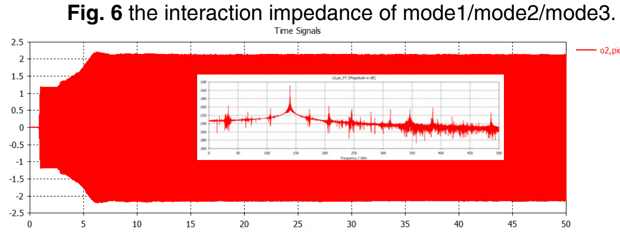
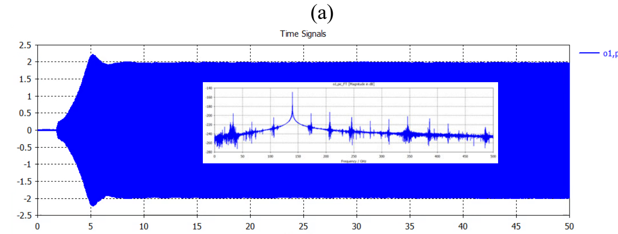


Fig. 6 the interaction impedance of mode1/mode2/mode3.



(a)



(b)

Fig. 7 normalized voltage of output signal at 140GHz(50ns). (a) forward wave (b) backward wave, and the inset show the frequency spectrum of the output signals.

Acknowledgment

This work is supported by National Natural Science Foundation of China (Grant No. 61771105 and 61921002) and Fundamental Research Funds for Central Universities (Grant No : 2672018ZYGX2018J037).

References

[1] L. Gao, Y. Hu, X. Zhu, Q. Hu, J. Li, and B. Li, “Investigation of terahertz radiation based on forward and backward wave feedback circuit,” *Physics of Plasmas,* vol. 26, no. 11, pp. 113104. 2019.