Concept and Design of the Terahertz Vacuum Electronic Amplifier Integrated on a Chip

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Abstract: *In this paper, the concept and design of the terahertz (THz) vacuum electronic amplifier (VEA) integrated on a chip is proposed. The THz VEA is driven by chip-scale cold cathodes and a cascade amplifier array (CAA). Based on the concept, an integrated travelling wave tube amplifier operating in the range of 200-500 GHz is designed. Particle-in-cell (PIC) simulation results show the integrated travelling wave tube produces a saturation output power of 2.76 W with a saturation gain of 23 dB at 400 GHz. The proposed concept paves a promising way for the VEA miniaturization and integration.*

Keywords: vacuum electronic amplifier; on-a-chip; terahertz; array integration; cold cathode.

Introduction

In recent years, the concept of system on a chip (SOC) has been extended from the integrated circuits to other fields, such as lab on a chip and radar on a chip [1][2]. As the SOC has merits of high integration, low-power consumption, small dimension and high reliability, it has become an effective way for system miniaturization. To minimize the dimension of vacuum electronic devices, we proposed the concept of the terahertz (THz) vacuum electronic amplifier (VEA) integrated on a chip. The integrated VEA comprises a cascade amplifier array (CAA) and cold cathodes. It can produce watt-level output power, which is beyond the output ability of current solid-state circuits, in the THz band [3]. The structure of this concept is easy to extend and is suitable for large-scale integration. Based on the concept above, an integrated travelling wave tube (TWT) operating in the range of 200-500 GHz has been designed and carried out by particle-in-cell (PIC) simulation.

Concept of the integrated VEA

Fig. 1 shows the schematic diagram of the THz VEA integrated on a chip. The structure contains a CAA, a series of field emission array cold cathodes and micro-collectors, all of which are integrated on a single chip. The field emission array cold cathodes provide high current sheet electron beams with a current density reaching hundreds of A/cm^2 [4]. The sheet electron beam then interacts with the surface wave of the meander line slow wave structure (SWS) and the amplified output of each cascade SWS cell is guided to the input of the next cell by microstrip line. Thus, the cascade amplification is achieved. To design a CAA with the targeted output power, the input-output power curve of a single SWS needs to be simulated and optimized firstly. When the saturation output power of the single SWS achieves the target, the cascade number, the input and output power of each cascade SWS cell are determined according to the input-output power curve.

The merits of the proposed design are high integration and high output power. As the dimension of the SWS is associated with the operating frequency range, the THz integrated VEA can be developed in the micron scale [5]. The field emission array cold cathodes have been widely used in vacuum electronic devices and can be integrated on the substrate as shown in Fig. 1 [6]. Thus, Large-scale integration of the VEA can be easily achieved through current microfabrication technology. With appropriate current density, SWS length and cascade number chosen, the integrated VEA is capable to produce watt-level output power in the THz band. The performance of the structure has been tested by PIC simulation and the design purpose is achieved.

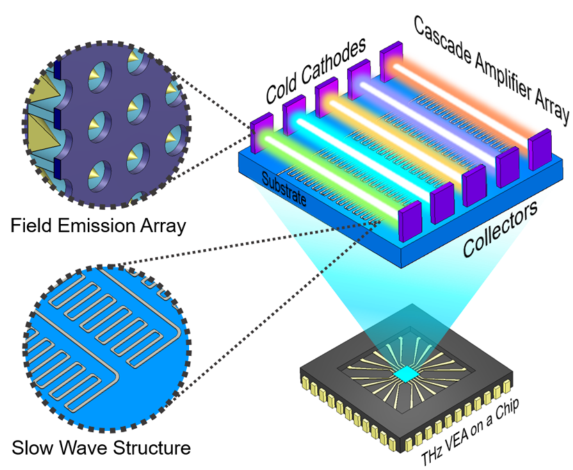

Figure 1. Concept scheme of the proposed THz VEA on a chip.

Particle-in-cell (PIC) simulation

A CAA including 5 SWS cells is used to achieve the beam-wave interaction in this section. The dispersion characteristic and the longitudinal E-field component of different modes are presented in Fig. 2. The mode 1 is the operating mode and the mode 2 is the competitive mode. The phase velocity of the fundamental wave of the mode 1 varies from 0.148c (5700 eV) to 0.150c (5850 eV) in the range of 200-500 GHz. It proves the synchronization between the electron beam and the mode 1 in a wide operating bandwidth. The beam voltage is 5950 V to avoid oscillation.

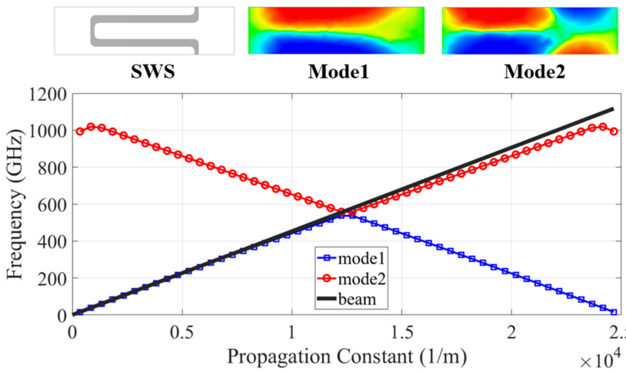

Figure 2. Dispersion and longitudinal E-field component of different modes.

The PIC simulation of the integrated TWT has been carried out by CST. Fig. 3 (a) shows the CAA structure containing 5 identical SWS cells. Each cell in the simulation was driven by a 5950 V, 4.5 mA beam emitted from a cold cathode of 90 μm×30 μm. Fig. 3 (b) and Fig. 3 (c) respectively show five modulated sheet electron beams and the cascade amplification of the E-field. In the frequency range of 200-500 GHz, the S_{11} of a single cell is less than -30 dB and the S_{21} is higher than -1 dB. Fig. 4 shows the input-output power curve of the CAA at 400 GHz. When the input power is 5 mW, the CAA produces an output power of 2.24 W with corresponding gain and efficiency of 26.5 dB and 1.67%, respectively. When the input power reaches 14 mW, the saturation output power reaches 2.76 W with corresponding saturation gain and efficiency of 22.9 dB and 2.06%, respectively. Since the output power of the solid-state circuits is below the watt level in the THz band, this result shows that the integrated VEA has a huge advantage over solid-state circuits in THz power generation.

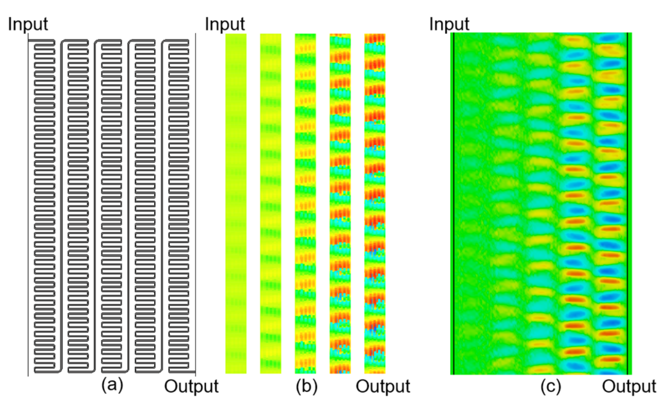

Figure 3. (a) The CAA structure. (b) Five modulated sheet electron beams. (c) Amplified E-field in the PIC simulation.

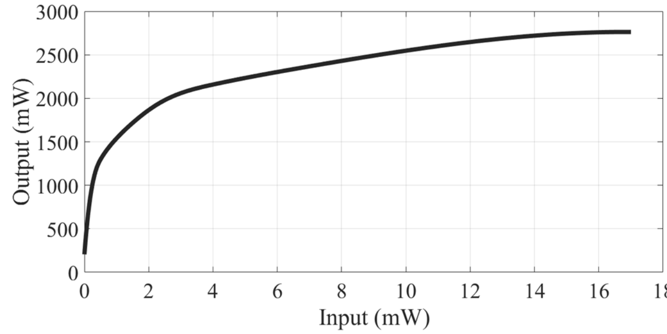

Figure 4. The input-output power curve at 400 GHz.

Conclusion

The concept of the THz VEA integrated on a chip is proposed. An integrated TWT with a five-cells CAA operating in the range of 200-500 GHz is designed to demonstrate the concept. The results of PIC simulation show the CAA can produce a saturation output power of 2.76 W at the frequency of 400 GHz. The integrated VEA is suitable for large-scale integration similar to the semiconductor circuits. Due to the advantages of small dimension, high power, wide tuning bandwidth, it is promising to be widely used for THz communication and biological imaging.

Acknowledgements

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References

1. P. S. Dittrich and A. Manz, "Lab-on-a-chip: microfluidics in drug discovery," *Nature Reviews Drug Discovery*, vol. 5, no. 3, pp. 210-218, 2006.
2. M. Li, R. J. Evans, E. Skafidas, B. Moran, "Radar-on-a-Chip (ROACH)," in 2010 IEEE National Radar Conference Proceedings, pp. 1224-1228.
3. L. A. Samoska, "An Overview of Solid-State Integrated Circuit Amplifiers in the Submillimeter-Wave and THz Regime," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 9-24, 2011.
4. N. S. Xu and S. E. Huq, "Novel cold cathode materials and applications," *Materials Science & Engineering R-Reports*, vol. 48, no. 2-5, pp. 47-189, 2005.
5. V. L. Granatstein, R. K. Parker, and C. M. Armstrong, "Vacuum electronics at the dawn of the twenty-first century," *Proceedings of the IEEE*, vol. 87, no. 5, pp. 702-716, 1999.
6. J. H. Booske, R. J. Dobbs and C. D. Joye, "Vacuum electronic high power terahertz sources," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 54–75, 2011.