Vacuum Electronic Devices

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Outline

1 Overview
   - Overview
   - History

2 Devices
   - Magnetron
   - Traveling Wave Tube - TWT
   - Backward wave oscillator - BWO
   - Klystron
   - Inductive output tubes - IOT
   - Gyrotron
   - Low frequency tubes

3 Future

4 Selected paper 1

5 Selected paper 2
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Overview

- Vacuum electronic devices produce coherent electromagnetic radiation through the interaction of an electron beam with an electromagnetic structure

- Applications include
  - Radar
  - Communications (terrestrial and space)
  - Fusion
  - Industrial processing
  - Medicine
  - Microwave ovens

- Multidisciplinary field. Advances driven by innovations in electromagnetic design and beam-wave interaction structures, as well as thermal management, new materials, fabrication and computational techniques
Many of the devices were invented during or just after World War II. These were all **Slow Wave** devices. During the 1950s, civil applications were developed. All these devices have been further developed to provide higher power and frequency, greater efficiency, and reduced size. A hybrid vacuum/solid-state microwave power module (MPM) was recently developed [1].
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Magnetron

- Cheap
- Frequency drift
- Used in civil radars, microwave ovens
- Pulsed or continuous operation
- <1GHz to 120GHz, 5MW/4kW peak/avg power

[Figure: Magnetron cross section [2] [3]]

Electrons from a hot filament would travel radially to the outside ring if it were not for the magnetic field. The magnetic force deflects them in the sense shown and they tend to sweep around the circle. In so doing, they "pump" the natural resonant frequency of the cavities. The currents around the resonant cavities cause them to radiate electromagnetic energy at that resonant frequency.
Traveling Wave Tube - TWT

- Wide bandwidth
- Reliable
- Used in military radars, space communications
- Efficiency (>73%)
- Max frequency 50-100GHz

Figure: Cross section, beam propagation [4] [5]
Backward wave oscillator - BWO

- Similar to TWT, but no RF in
- Two types, M and O
- Voltage controlled frequency
- M-type, high output power, O-type <1W
- O-type have very low noise

Figure: M-BWO [6]
Klystron

- Fixed frequency
- Two cavities - Input/bouncer and Output/catcher
- More catchers increase efficiency -> EIK
- TV transmitters, radar, satellite
- 75 MW output (pulsed)
- Up to 280GHz
- Reliable

Figure: Cross section [7]
Inductive output tubes - IOT

- Invented 1938
- Widely used since 1980 - replaced Klystrons
- 30 kW continuous power
- Efficiency 60% with 8VSB

Figure: IOT [8] [9]
Gyrotron

- Gyro device - FWS - bremsstrahlung
- 1GHz to 1THz
- Heaters for fusion reactors
- Also for industrial, medical and warfare

Figure: Iter gyrotron [10] [11]
Audio / Music applications

One field where vacuum tubes is superior to solid state is in guitar amplifiers. An amplifier built to distort benefits from the more pleasant overtones of tubes.
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5. Selected paper 2
Future

1. Terahertz gap needs to be filled
2. Normal linear SWS will have difficulties reaching higher frequencies
3. Novel materials, meta materials
4. Free electron Laser (FEL) promise high power at millimeter to X-ray wavelengths [1]
Future

Figure: The Terahertz gap [12]
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$V_{DS} = 10\,V$

Mean Free Path in air is too short

First attempt managed 460GHz

Compatible with CMOS fabrication

Design of the tips crucial
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High frequency VED structures is hampered by the challenges of high precision three-dimensional machining required for shorter wavelengths, and also by limits in maximum beam dimensions and current.

By using electromagnetic metamaterials (MTMs) some of these challenges can be addressed.

This paper demonstrates that when a SWS is loaded with epsilon negative metamaterial (ENG) slabs periodically, it’s band diagram is shifted to higher frequencies.

A metamaterial is a material engineered to have properties not yet found in nature. Often arranged in a repeating pattern, at microscopic or smaller scale that are less than the wavelengths of the phenomena they influence.

This specific metamaterial (ENG) have negative $\varepsilon_r$ and positive $\mu_r$. 

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Result

- \( f_0 = 48\text{GHz} \) for the unloaded unit cell
- Cutoff \( f_c = f_0 / 1.25 \)
- Wideband without ENG
- Narrowband with ENG
- ENG dispersive permittivity:
  \[ \varepsilon_r = \varepsilon_\infty - \left( \frac{f_p}{f} \right)^2, \]
  with \( f_p = 281.6\text{GHz} \)
- Physical dimensions 35% larger, so higher beam current is possible

Figure: Unit cell of ENG loaded TWT

Figure: Phase velocities
References I


References II


References III

