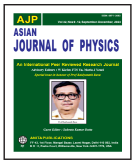

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Autobiographic account of my induction and furtherance in research in the area of vacuum electronic devices

Baidyanath Basu

Ex-Professor, IIT-BHU, Varanasi, India

Supreme Knowledge Foundation Group of Institutions, 1 Khan Road, Mankundu-712 139,W B, India

The author described in an autobiographical account how he entered and furthered his R&D in the arena of vacuum electronic devices (VEDs). He has also described his service to various organisations during the R&D phase of various VEDs. How the basic backgrounds of mathematics, physics and electromagnetic theory were infused in him has been described. The superiority of VEDs over their solid state device (SSD) counterparts was established in the high power, high frequency domain, in particular, in strategic areas, despite the competitive incursion of SSDs into the domain of VEDs. The potential of R&D in VEDs can be seen from the global trends categorized in six groups.

In the microwave frequency range 'vacuum electronic devices' (VEDs) are synonymous with 'microwave tubes'. The underlying principles of these devices are based on electromagnetic theory which in turn is based on the subject of electricity and magnetism, which we start learning in our Physics class from our school days. However, in my case, I did not get an opportunity to learn Physics in my school—Vivekananda School, governed by Ramakrishna Mission, at Sakchi in my hometown Jamshedpur situated in the erstwhile state of Bihar, India. The reason for not getting this opportunity is given in the following few lines. Based on the results of class VII in the primary school (from class I to VII), the students were allowed to choose their options between 'science' and 'arts' streams in the high school (from class VIII to XI). In our high school, there were two sections in the 'science' stream and a single section in the 'arts' stream. Most of the students were interested to join the science stream. In this competitive scenario, I could not get a berth in the science stream, and I was admitted to the arts stream. There, I studied the subjects, namely, elementary mathematics, economics, civics, geography, etc. instead of the subjects, namely, elementary mathematics, advanced mathematics, physics, chemistry, etc., studied by my classmates in the science stream. Even then, it so happened that beyond my school days I studied science, engineering and technology and furthered in my research in the area of VEDs as presented in this autobiographic note. In the subsequent sections, I have given the basic background of mathematics, physics and electromagnetic theory that I gained (section 1), an account of my doctoral research (section 2), my service to various organisations while dedicating to VED research (section 3), the general competition between solid state devices and VEDs (section 4), the global trends in VED research and development (section 5) and the conclusions of the present note apprising the readers of the ever expanding scope of VEDs in the high power, high frequency domain at the end.

1 Basic backgrounds of mathematics, physics and electromagnetic theory instilled in me

Mathematical background helps one to grasp the subject of physics encompassing electromagnetic theory and hence the underlying principles of VEDs. However, my mother—who brought up our family of

Corresponding author

e mail: bnbasu.india@gmail.com (Baidyanath Basu)

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three brothers and two sisters when I had lost my father at two years of my age, and who was a teacher in the primary section of our school—home-schooled me in mathematics. To my mother, I dedicated one of the books authored by me and published by World Scientific publishers [1], the first part of which deals with electromagnetic theory. To my elder sister, who was a teacher in the high school section of our school, and who also taught me mathematics at our home in the high school level, I dedicated another book, authored by me and published by Universities Press [2], which also deals with the subject of electromagnetic theory. I am also indebted to the mathematics teacher Mr Biren Mukherjee, who later became a Sanyasi of Ram Krishna Mission, for enthusing in me the interest for the subject of mathematics.

Photo 1. Prof B N Basu

I was thrilled to see the harmony and symmetry in the vector calculus expressions of mathematics in the generalized curvilinear system of coordinates for the gradient of a scalar quantity (such as electric potential), divergence of a vector quantity (such as electric field), curl of a vector quantity (such as electric field), and Laplacian of a scalar quantity (such as electric potential). Interestingly, if we know one of the three terms of these expressions, we can permute it to derive the remaining two. Subsequently, from any one of these expressions in the generalized curvilinear system of coordinates, we can write, as a special case, the corresponding expression in the rectangular, cylindrical or spherical polar system of coordinates as appropriate to the geometry of the problem at hand. In fact, with the help of this vector calculus of mathematics, it was possible for Oliver Heaviside to reduce as many as twenty original equations in twenty variables, given by James Clerk Maxwell, to famous four equations—known as Maxwell's equations—which, according to J R Whinnery, are: 'simple enough to imprint on a T-shirt, and yet rich enough to provide new insights throughout a lifetime of study.' Based on my obtaining good marks in elementary mathematics, I was the only student, with arts-stream background in school, admitted into Intermediate Science at Jamshedpur Cooperative College in my hometown Jamshedpur in the erstwhile Bihar, India. In building the foundation of my career in science, engineering and technology of VEDs, my Intermediate Science classmates, who had come from the science stream in school, immensely helped me. They helped me to follow Physics in Intermediate Science class. There I was overwhelmed by the lectures of Professor Madan Mohan Mahanty in Physics. Further, there I got the opportunity to have Professor Adhir Banerjee as our teacher who also helped me to understand Physics both in theory and practical classes. After this, I was selected for admission into the Department of Electronics and Electrical Communication Engineering (E&ECE) of Indian Institute of Technology (IIT), Kharagpur. However, under financial constraints, I could not join IIT-Kharagpur and instead I joined the B Sc Physics (Honours) course offered at the Vidyasagar College of Calcutta University, Kolkata. There, I had the privilege of being taught by teachers par excellence: the subject of electricity and magnetism by Professor H P Dey and the subject of optics by Professor C C Banerjee. After graduating with

Honours, I did my B Tech and M Tech in Radiophysics and Electronics (RPE) of Calcutta University at the Institute of RPE. There, I came across world famous teachers and researchers. Professor N B Chakrabarty taught us electromagnetic theory. I was spellbound by the brilliant teaching of Professor B R Nag, who taught us applied electromagnetics, including waveguides.

2 My Doctoral Research

Obtaining my B Tech and M Tech degrees in RPE of Calcutta University at the Institute of RPE, I joined the same Institute to carry out my doctoral research under the mentorship of Professor Mrinal Kanti Das Gupta. Professor Das Gupta had carried out his own doctoral research at the Manchester University under the mentorship of the Nobel Laureate, PMS Blackett. Professor Das Gupta became internationally known when he, along with his co-worker RC Jennison, discovered the existence of a black hole at the centre of the Cygnus. The area of my research with Professor Das Gupta as my mentor at the Institute of RPE was solar radiation—the radiation that is caused by the conversion of the energy of moving electrons (electron beam) through the mechanisms such as bremsstrahlung emission and electron cyclotron resonance maser emission. Interestingly, the conversion of the energy of the electron beam takes place also in VEDs—potential energy conversion in devices such as magnetron, while kinetic energy conversion in devices such as travelling-wave tube (TWT). Also, electron cyclotron resonance maser instability takes place in a gyro-device such as gyrotron, while bremsstrahlung radiation takes when the electrons accelerate or decelerate (bremsstrahlung) in electric or magnetic field—typically, in a virtual cathode oscillator in electric field, and in a gyrotron in magnetic field.

However, under some unavoidable circumstances of domestic affairs, I had to leave my doctoral research at the Institute of RPE, when after taking kind permission of Professor Das Gupta I left the Institute of RPE to join DRDO—Defence Electronics Research Laboratory (DLRL), Hyderabad and got posted at its field research station (FRS): Indian Naval Ship (INS) Valsura, Jamnagar, Gujarat. There, I was investigating into the problem of false detection in radar caused by abnormal refraction in atmosphere. Working there for some time, I joined E&ECE Department of IIT, Kharagpur, under the tutelage of Professor Nirmal Baran Chakrabarty for my doctoral research. Professor Chakrabarty was well known in the area of communication engineering. Versatile genius, he was a D Sc of Calcutta University in the area of communication engineering; founder of the microelectronics centre at IIT-Kharagpur; and contributor to the early research in India in the area of VEDs at the Institute of RPE, Calcutta University. In fact, Professor Chakrabarti was a scientist and engineer in a single person reminding us what William Cecil Dampier said, "*There is only one nature — the division into science and engineering is a human imposition, not a natural one. Indeed, the division is a human failure; it reflects our limited capacity to comprehend the whole*."

I became at that point of time interested to carry out my doctoral research in the area of communication engineering with Professor Chakrabarti as my mentor at IIT-Kharagpur. However, it so happened that, when I had met Professor Chakrabarti at IIT-Kharagpur to probe into the possibility of doing my doctoral research under his mentorship in the area of communication engineering (while I was still employed at DLRL-FRS: INS-Valsura, Jamnagar), Professor Chakrabarti saw in my hand the book titled "Plasma Physics" by S Chandrasekhar. This prompted him to fix my doctoral research topic as: 'Nonlinear effects such as harmonic generation and frequency mixing in double-beam and beam-plasma amplifier' instead of a topic of communication engineering. It reminded me the doctoral research topic in the area of solar radiation Professor Mrinal Kanti Das Gupta had given me at the Institute of RPE of Calcutta University before I left the Institute. The topic dealt with fundamental and second harmonic radiation in solar bursts. What a coincidence in the doctoral research topics proposed by my two mentors—Professor Das Gupta at the Institute of RPE, Kolkata and Professor Chakrabarti at IIT, Kharagpur. And yet another interesting and surprising coincidence was that the name of one of my mentors at Kolkata was "Mrinal" (Professor Das Gupta) and that of another mentor at Kharagpur was "Nirmal" (Professor Chakrabarti), which are anagrams of each other. It so happened that although I carried out most of my doctoral research at IIT, Kharagpur, I submitted my doctoral thesis, at the instance of my mentor Professor Chakrabarti, to the Institute of RPE, and obtained my Ph D degree from Calcutta University. While on the verge of completing my doctoral research, I joined the teaching faculty of Regional Institute of Technology (RIT) (now known as National Institute of Technology), Jamshedpur.

3 My service to various organisations in the field of VEDs

I joined the Physics Department of RIT, though I had the option of joining its Electrical Engineering Department, too. There, I was fortunate to have Professor M M Mahanty, who had taught me Physics in Intermediate Science, as my colleague. I also came across Professor Lalit Kishore, who was a Ph D from University of Southampton, as Head of Department, who greatly helped me in building my concepts of electromagnetic theory. Thereafter, I was employed at various teaching and research organizations and carried out my research in the area of VEDs. Thus, for a short period I left RIT, Jamshedpur and worked as a scientist at CSIR-Central Electronics Engineering Research Institute (CEERI), Pilani. There, I was one of the members of a team led by Dr S N Joshi in the Vacuum Tube Division headed by Dr S S S Agarwala, to which the credit goes to the development of the first TWT in India under the guidance of Dr Agarwala. At the instance of Dr Amarjit Singh, the then Director of CEERI, we experimentally characterized the TWT developed by us with respect to its various output parameters including the AM-to-PM conversation coefficient. This led ISRO to sponsor projects for developing space-TWTs at CEERI. I co-chaired, along with the ISRO Chairman, a committee for monitoring an ISRO-sponsored project at CEERI for developing space-TWTs led by Dr S K Ghosh, who was our Ph D student at Banaras Hindu University (BHU), Varanasi. During my short stay at CEERI, motivated by Dr Agarwala I wrote two internal reports on the analysis of helical slow-wave structure of a TWT—one based on equivalent circuit analysis [3] and another on field analysis [4]. Incidentally, I dedicated one of the books authored by me [5] to Dr Agarwala. These two internal reports [3,4] became the starting point of the analysis of innovative design of wideband helix-TWTs for electronic warfare applications in India and abroad, at that point of time when the simulation tools were not available for this purpose. After working for about ten months at CEERI, Pilani I came back to RIT, Jamshedpur and continued to work in the area of the analysis of helical slow-wave structures with Dr A K Sinha, who was then a research scholar there. Later on, I continued to carry out research in collaboration with the scientists of CEERI, Pilani as Distinguished Visiting Scientist of CSIR while I was in the faculty of the Electronics Engineering Department of BHU. Dr Sinha joined CEERI, Pilani and continued to carry out research with me in the area of helical slow-wave structures of TWTs. Dr. Sinha at CEERI joined Dr R K Gupta, Dr R S Raju, Dr R K Sharma and Dr S K Ghosh in developing electronic warfare and space-TWTs in the sponsored projects under the guidance of Dr S N Joshi. Eventually, Dr Sinha and Dr Ghosh became internationally acclaimed for their expertise in the area of the analysis of helical slow-wave structures. Furthermore, Dr Sinha established the Gyrotron Lab at CEERI under a project of Department of Science and Technology (DST) with the support from Dr S N Joshi and Dr Chandra Shekhar, the erstwhile Director of CEERI. The said project was a multi-institutional project for the development of the first gyrotron in India involving five organisations—(i) Centre of Research in Microwave Tubes (CRMT), Electronics Engineering Department, Institute of Technology, BHU (now known as IIT-BHU), (ii) Indian Institute of Technology, Roorkee, (iii) Society for Applied Microwave Electronics Engineering and Research (SAMEER), (iv) Institute for Plasma Physics (IPR), Gandhinagar, and (v) CEERI, Pilani (nodal institution of the project) under the overall supervision of Dr S N Joshi of CEERI as its the overall coordinator. In a meeting of DST, Professor R K Jha of Electronics Engineering Department, BHU, presented a position paper prepared by me at Centre of Research in Microwave Tubes (CRMT) of the Department based on which the above multi-institutional project was granted. I actively participated in monitoring the project as a member of a steering committee of DST.

I joined Electronics Engineering Department of BHU (now known as IIT-BHU) on invitation from Professor N C Vaidya, the erstwhile Head of Department, to help him to nurture CRMT in the Department. Incidentally, I dedicated one of the books authored by me to Professor Vaidya [6]. Based on my lectures in the undergraduate and postgraduate programmes of the Department I authored two books [1,2]. Dr P K Jain, one of my colleagues in the Department, and his B Tech classmate Professor Akhlesh Lakhtakia of Pennsylvania State University took a key role to publish the first one [1] of these two books under the imprint of World Scientific Publishing Co. Inc. (Singapore, New Jersey, London, Hong Kong) in 1996. While the second one of these two books deals with the engineering electromagnetics [2], the first one in its first part deals with electromagnetic theory and in its second part deals with beam-wave electronics [1].

I developed a collaborative link with DRDO – Microwave Tube Research and Development Centre (MTRDC). Two of our postgraduate as well as doctoral students, Dr Sudhir Kamath and Dr Subrata Kumar Datta (who is guest-editing the present special issue of the journal), joined DRDO-MTRDC to assist Dr M D Rajnarayan, the erstwhile Director of DRDO-MTRDC, to nurture MTRDC. Eventually, they became scientists of national importance. As a student, Sudhir worked with us to synthesize the shapes of the Pierce electron guns using conformal transformation technique. Subrata used nonlinear Eulerian hydrodynamic technique to study harmonic generation and intermodulation distortion in a TWT—the technique which I myself used in studying nonlinear effects in double-stream amplifier and beam-plasma amplifier during my own doctoral research under the mentorship of Professor N B Chakrabarty at IIT, Kharagpur.

Dr James A Dayton (Jr), who retired from NASA and joined Hughes Electron Dynamics, Torrance, inspired me by his invitation to serve at the first Technical Committee on Vacuum Devices of IEEE-Electron Devices Society as a charter member of the Committee. In that capacity, I served the Committee from 1998 to 2003 and represented our country, India for the first time. I am indebted to Dr Dayton for introducing our country and myself to the electron devices community of the world. Incidentally, Dr Dayton, in 2006, received the J R. Pierce award for excellence in vacuum electronics of IEEE Electron Devices Society. Dr D T Swift-Hook, former Head of Research Division of Central Electricity Generating Board, London, through a letter, suggested me how I could use a tapered-cross-section dielectric helix-support rods to implement my idea of surrounding a helix by a number of dielectric tubes of different optimally increasing permittivity values in the radial outward direction, for dispersion-shaping a helical slow-wave structure for the purpose of widening the bandwidth of a TWT. Further, Dr D T Swift-Hook has esteem for me because in my publication of research papers I cited one of his papers (Swift-Hook D T, 1958, “Dispersion curves for a helix in a glass tube,” IEE, vol 105B, pp 747–755) maximum number of times in the world. Professor Alexander Scott Gilmour, (Jr) responded to my request and authored a paper entitled “An overview of my efforts to bridge the gap in the microwave tube area between what universities provide and what the industry needs” in the Special Issue on “Microwave Tubes and Applications” in the Journal of Electromagnetic Waves and Applications (Taylor and Francis) (issue 17, vol 31, 2017), which I guest-edited. Dr Gilmour, on my request, gave his consent to write a book in the “IOP Series in Electromagnetics and Metamaterials” of IOP Publishing Ltd, Bristol, which I am editing. However, due to his indisposition, he could not take up this. Incidentally, Dr Gilmour in 2018 received the J R Pierce award for excellence in vacuum electronics of IEEE Electron Devices Society. Professor R G Carter invited me in 1993 to the Lancaster University in an academic link and interchange scheme of the British Council. I was adopted the third partner with the original two partners: CEERI, Pilani and Lancaster University. I developed at Lancaster University an improved theory of measurement on helical slow-wave structure of a TWT based on non-resonant perturbation technique. Incidentally, Professor Carter, in 2009, received the J R Pierce award as well. Professor Gun-Sik Park has been in close interaction with me since 2001, when he started his R&D activities at Seoul National University (SNU), Republic of Korea in the area of VEDs. My collaboration with him and his team is evidenced by publications. I was instrumental in establishing an MOU between SNU, Republic of Korea and

CSIR-CEERI, India. Professor Park also received the J R Pierce award in 2021. Professor Manfred Thumm provided his immense conceptual support to us during our effort to develop the first gyrotron in India. He invited me to visit Karlsruhe Institute, Germany, when he was the Director of the Institute. Both Professor Thumm and I delivered tutorial lectures in the areas of gyrotrons and TWTs, respectively, in 2003-IVEC held at Seoul which was general-chaired by Professor Gun-Sik Park. On my request, Professor Thumm delivered a webinar lecture on the platform of the Group of VED Thinkers, which I established in India. Professor Thumm was the 2008 J R Pierce awardee for his immense contribution to vacuum electronics. Professor John Jelonnek was the Director of Karlsruhe Institute of Technology, Germany, when I visited the Institute in November 2011 for academic interactions and when Professor Manfred Thumm had just handed over the charge as the Director of the Institute to Professor Jelonnek. I delivered two lectures—one on some broadbanding aspects of slow-wave and fast-wave traveling-wave tubes on November 15, 2011 and the other on scenario of development of microwave tubes in India on November 17, 2011. On my request, Professor Jelonnek delivered a webinar lecture on the platform of the Group of VED Thinkers. Professor Edl Schamiloglu presented me the hard copy of his book entitled 'High Power Microwaves' co-authored with James Benford and John A Swegle. Also, Professor Schamiloglu wrote his scholarly 'Foreword' of my book entitled 'High Power Microwave Tubes: Basics and Trends' co-authored with Vishal Kesari [6]. Professor Zhaoyun Duan of University of Electronic Science and Technology of China (UESTC) at Chengdu in China interacted with me in 2005 through email, and jointly authored a research paper on accurate tape-helix model of analysis of attenuator coated helical slow-wave structure in 2006. Five years later, we met him at Bangalore IVEC-2011. On invitation from Professor Duan, I spent the summer of 2018 delivering lectures to the Ph D students of UESTC. Thereafter, we have been extensively carrying out collaborative research until today and jointly authored a good number of research papers in journals and also contributed to book chapters. It has been since Bangalore IVEC-2011—and even much before that when he had been citing in his own papers our work in the area of analysis of helical slow-wave structures—I have been in contact with Professor Claudio Paoloni, Head of Engineering Department, Professor of Electronics and Cockcroft Chair of Lancaster University. Professor Paoloni has also delivered a webinar lecture on the platform of the Group of VED Thinkers.

4 Competition between Solid State and Vacuum Electronic Devices

VED designers need to be aware of the competitive incursion of solid state devices (SSDs) in the domain of VEDs making cognition of the relative strengths of SSDs and VEDs [6], described point-wise as follows.

(1) Heat produced by electron-atom collision is lesser in a VED than in an SSD, since in the former such collision takes place only at the collector unlike in the latter, where it takes place throughout the device volume.

(2) It is not required to operate a VED at a lower temperature for a longer device life, unlike an SSD.

(3) It is possible to recover energy out of waste beam of electrons in a VED for enhanced device efficiency, which is not possible in an SSD.

(4) The breakdown limit on maximum electric field inside a VED is higher than that inside an SSD.

(5) Unlike in a VED, the device performance at a higher temperature is degraded due to the dopant migrating excessively, the lattice becoming imperfect and electron mobility becoming reduced.

(6) In a VED, lower temperature operation for a longer life of the device is not required as is required in an SSD.

(7) While, in general, it is possible to operate a VED at a higher temperature, it is possible, though to a limited extent, to operate an SSD at a higher temperature using wide-band-gap semiconductors such as SiC and GaN.

(8) As compared to an SSD, a VED which has a higher interaction volume enjoys higher power handling capability.

(9) Since in a VED the electron beam may be pulsed in the region separated from the interaction region, it is possible to obtain higher peak pulsed power in such a device than in an SSD.

(10) For higher RF output powers, a larger package size is required in an SSD in view of the requirement of power combining of multiple devices, which is however not required in a VED since a single device is good enough for the same purpose.

(11) The base plate size of the device—which is determined by the cooling efficiency that increases with the temperature difference between the hot surface of the device and the cool environment as well as with the surface area of the hot surface—is smaller for a VED than for an SSD.

(12) A VED can be hardened against radiation and made tolerant to temperature and mechanical extremes, unlike an SSD.

(13) An SSD enjoys a higher signal processing speed than a VED.

(14) An SSD is superior to a VED from the standpoint of lower noise figure, better linearity, lesser warm-up delay, lesser process cost, higher potential for batch production, lesser periodic maintenance, lesser high-voltage power supply requirement, and so on.

In the ‘high-power, high-frequency domain’ domain of applications, SSDs cannot match VEDs. Moreover, the technologies of these two devices can work in tandem to realize high power THz ‘vacuum microelectronic’ devices. Furthermore, a VED and an SSD (to be more specific, a TWT power booster and a solid state power amplifier) can make ‘peaceful coexistence’ in what is known as a microwave power module (MPM). The MPM is hardly of the size of a laptop, in which these devices coexist, with equal gain sharing, along with an electronic power conditioner.

Gilmour, in a paper written by him on my invitation [7], reproduced a ‘satirical’ illustration in the form of a cartoon with a self-explanatory caption: “Why use a thousand mice when one horse can do the job?”, which was due to Rodney Vaughan presented in Microwave Power Tube Conference at Monterey, California in 1990. This presentation, which sharply criticized the attempt of replacing a single VED with a multiple of SSDs to obtain the desired RF output power level [7], had a strong impact on the VED and SSD communities. In continuation further, it is of relevance to mention an example in which an attempt to replace a space-TWT with its SSD counterpart did not succeed. This owes to the ‘mean time between failures’ of the former which cannot be attained by the latter [2]. Also, vacuum microelectronic technology such as X-ray lithography can be used to extend the high power and high frequency capability of VEDs to the terahertz regime and impart the batch production capability to them.

5 Global trends in VED research and development

According to me, there is a trend in research and development in VEDs, which can be categorized in six groups I-VI, as follows [6]:

Group I–

Conventional VEDs subject to continuous improvement in their performances: The conventional microwave tubes such as magnetron, TWT, klystron, etc. come within the purview of this group of VEDs. Thus, there is a global competition to widen the bandwidth of electronic warfare helix-TWTs by innovative dispersion control technique of helical slow-wave structure and similarly to improve the efficiency of space-TWTs by innovating helix pitch profiling and beam energy recovery using multi-stage depressed collectors. The other tubes under this group are: multi-beam klystron (MBK) (for high powers in a compact device); extended interaction klystron (for wider bandwidths and higher powers); extended interaction oscillator (in the mm-wave frequency regime); inductive output tube (klystrode) (for higher frequencies, higher powers and compactness); twystron (a combination of a TWT and a klystron for wider bandwidths); magnetron (with hole-and-slot-type cavities and echelon-type strapping/ vane-type, double-ring strapping) (space-harmonic type with cold cathode planar structure configurations for higher frequencies).

Group II–

VEDs accruing the advantages of both vacuum electronics and solid state electronics/solid state devices: The VEDs within the purview of this group are micro-fabricated tubes such as folded-waveguide TWT, klystrino, short-length helix-TWT for MPM, etc.

Group III–

Intensive relativistic electron beam (*IREB*) *driven VEDs in high power microwave* (*HPM*) *area* (*for making directed energy weapon, active denial system, etc.*): The VEDs within the purview of this group are: magnetron, klystron, RELTRON, backward-wave oscillator (BWO)—all relativistic; virtual cathode oscillator (VIRCATOR) and magnetically insulated line oscillator (MILO) in both of which no external magnetic field is required; orotron (radiation diffraction generator), multi-wave Cerenkov generator, etc.—all belonging to the Cerenkov radiation type of VEDs. The group brings within its purview the 'electromagnetic bomb' which is implemented by using a magnetic flux compression generator in conjunction with a VIRCATOR, etc.

Group IV–

Fast-wave VEDs: The VEDs of this category include conventional small-orbit gyrotron; high-harmonic large-orbit gyrotron (higher harmonics being required for lowering the magnetic field corresponding to cyclotron resonance at higher frequencies; vane-loaded gyrotron, coaxial-cavity gyrotron with corrugated, tapered-cross-section coaxial insert, photonic band gap gyrotron—all for mode rarefaction; quasi-optical gyrotron; gyro devices such as gyro-TWT (dielectric loaded, metal disc loaded, multi-sectioned—all for wider bandwidths), gyro-BWO, gyro-klystron, cyclotron auto-resonance maser (CARM) for higher powers and efficiencies and wider bandwidths without vane-loading, etc. of the cavity, gyro-twystrons, PHIGTRON (phase-coherent, harmonic multiplying, inverted gyro-twystron), peniotron (for higher efficiency), etc.

Group V–

Plasma assisted VEDs: The VEDs of this category accrue the advantages of plasma filling such as larger space-charge limiting current, thereby allowing for larger beam current transport and consequent larger device output power. The plasma filling also relaxes the required magnetic field in the device. Some of the devices in this category are: coupled-cavity TWT, gyrotron and slow-wave oscillator (PASOTRON) (—all plasma assisted).

Group VI–

Metamaterial assisted VEDs: Some of the devices in this category are: resistive-wall amplifier, TWT, BWO, backward-wave amplifier, klystron, MBK, etc. Metamaterial assistance in VEDs provides the device structure miniaturization, at one hand, at lower frequencies for device compactness, and, on the other hand, the structure enlargement at higher frequencies, thereby making the structure fabrication and thermal management of the device much easier.

Professor Pankaj Kumar Choudhury, the Editor-in-Chief of Special Issue of Journal of Electromagnetic Waves and Applications on Microwave Tubes and Applications, invited me to guest-edit the Special Issue of the Journal on "Microwave Tubes and Applications"; and Dr S K Datta and I wrote the relevant Guest Editorial of the issue. In that issue Dr A S Gilmour wrote about his efforts to bridge the gap in the microwave tube area (to be taken as synonymous with VED area) between what universities provide and what the industry needs [7]. I immensely value his efforts in the present context to make the study of VEDs of relevance vis-à-vis the actual requirements in industries.

A ‘needle’ (here, SSD) cannot do the work which a sword (here, VED) can do, and vice versa. Both have their relative merits and demerits. There are ample potential of research and development in VEDs categorized in five groups as can be seen from the global trends identified in this article. The strategic need for VEDs in the high power, high frequency domain will continue to make them important and make their horizon ever expanding.

References

1. Basu B N, Electromagnetic Theory and Applications in Beam-Wave Electronics, (World Scientific Publishing Co. Inc., Singapore, New Jersey, London, Hong Kong), 1996.
2. Basu B N, Engineering Electromagnetics Essentials, (Universities Press, Hyderabad), 2015.
3. CSIR-CEERI-IR-01/VT/78: Basu B N, Joshi S N: Equivalent circuit analysis of a helix in free space.
4. CSIR-CEERI-IR-02/VT/78: B. N. Basu: Field analysis of dielectric supported and shielded sheath helix
5. Basu B N, Technical Writing, (Prentice-Hall of India, New Delhi, India), 2007.
6. Kesari V, Basu B N, High Power Microwave Tubes: Basics and Trends, Vol 1, (Morgan and Claypool Publishers, San Rafael,California/Bristol: IOP Publishing), 2018.
7. Gilmour S, An overview of my efforts to bridge the gap in the microwave tube area between what universities provide and what the industry needs, in B N Basu (Guest Editor): Special Issue on Microwave Tubes and Applications: J. *Electromagn. Waves Appl*, 31(2017)1775–1785.

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Photo 2. Prof B N Basu