

# HBV DIODE MULTIPLIER DEVELOPMENTS FOR THZ APPLICATIONS

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## INTRODUCTION

The purpose of this paper is to review the Heterostructure-Barrier-Varactor (HBV) technology developments and the most significant results from these last years concerning frequency multiplying in millimetre and submillimetre waves range by odd harmonics generation. Details about diodes characteristics manufactured by the main laboratories in Europe and over the world, together with the different multiplier architectures designed and tested are furnished. A summary of the best performances obtained so far is given. The aim of this work is to set the basis for future developments for LO sources at THz frequencies, using an alternative technology to the GaAs Varactor diodes multipliers.

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# Historic and principle of the HBV diodes

The Heterostructure Barrier Varactor (HBV) has been invented 10 years ago by Kollberg and Rydberg [1], with the first denomination Quantum Barrier Varactor (QBV). These components have demonstrated to be strong candidate for high power frequency multipliers at millimetre and submillimetre wave frequencies.

## Principle of operation

The HBV diode is an unipolar device and consists of a symmetric layer structure. An undoped high band gap material (barrier) is sandwiched between two moderately n-doped, low band gap materials. The barrier prevents electron transport through the structure. Since the HBV has a symmetric capacitance-voltage (C-V) characteristic, it operates unbiased and will only produce odd harmonics when pumped with power at the fundamental frequency. This feature has the great advantage to avoid idler circuit design (to suppress even harmonics). When the diode is pumped, a depleted region builds up, causing a nonlinear capacitance voltage characteristic. Figure 1 shows the symmetrical C/V around 0V and asymmetrical I/V curve of an HBV diode [2]. However, the main limitation of the bandwidth of this type of devices comes from the high-Q coefficient.

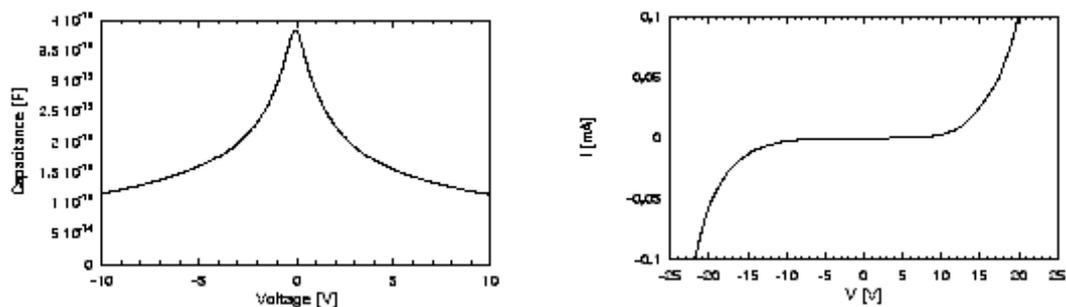


Figure 1a & 1b : typical C/V and I/V curves taken from an HBV diode measured at Chalmers [2].

An important advantage of the HBV diode compared to the Schottky varactor diode is that several barriers can be epitaxially stacked, which increases the power handling capability considerably [3]. Figure 2 shows the different stacking layers of semiconductors corresponding to 2 HBV diodes in series, performed at the IEMN (*Institut d'Electronique et de Microelectronique du Nord* in Lille-France).

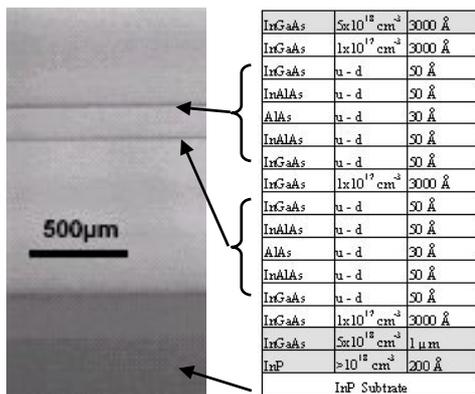


Figure 2 : view of the stacking layers corresponding to 2 HBV diodes in serie, performed at the IEMN[3].

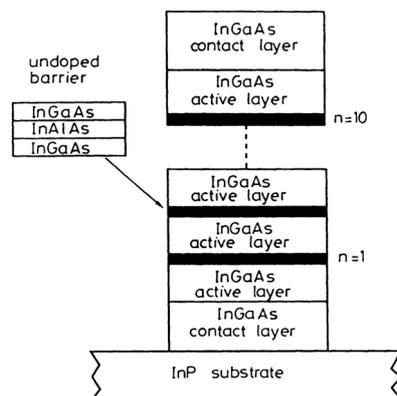


Figure 3 : the lattice matched MSQBV layer structure. 90mW of output power has been produced at 93GHz[4].

It has been demonstrated by a Canadian team [4] with a process of Multi-Stacked Quantum Barrier Varactors (MSQBV) that stacking 10 active junctions could permit to rise an output power as high as 90mW at 93 GHz (see Figure 3).

We will now focus on the different materials and techniques used for frequency multiplying (x3 for triplers and x5 for quintuplers) with HBV diodes.

## Technology overview of frequency multipliers using HBV diodes

In this sections, we review the HBV diodes fabrication and the way they are mounted in multiplier structures.

Several kinds of semi-conducting material III-IV are used to fabricate the HBV diodes : InP-based (developed at the IEMN and the University of Virginia), and GaAs-based (developed at Chalmers University and the University of Darmstadt) materials. Both technologies have shown very good results. Then, contacting the HBV junction to the rest of the circuit is done in the following ways : whisker-contacting, already used since ages for Schottky diodes mixers, and planar contacting techniques, which has been well developed since 10 years. Nowadays, it is assumed that planar-contacted HBV diodes are more reliable and have more reproducible performances than whisker-contacted diodes, allowing a full integration of the circuit together with the HBV diode. However, novel whisker designs have still some advantages in term of junction heat sink. We will illustrate now our purpose by giving the most efficient multipliers built and tested using these technologies.

### Waveguide tripler developments

The waveguide tripler architecture allows an accurate coupling of the input signal to the diodes and output signal from the diodes using guided propagation structures. Inside these waveguides, the HBV diodes are mounted in different ways. The main ones which are presented herein are : the cross-waveguide mount, the finline mount, and the whisker-contacted mount.

### InP-based planar diodes HBV triplers

The IEMN, in collaboration with the Observatoire de Paris and ASTRUM with ESA & CNES contracts, has developed a fully integrated monolithic circuit incorporating InP-based planar HBV diodes [5][6]. A serie of 2x2 barriers constituting a serie of 4 HBV diodes are connected in series with planar air-bridges, as shown in Figure 4a. The monolithic circuit is mounted in a cross-waveguide bloc, as shown in Figure 4b.

This technology has shown very good performances at 288 GHz [5], with a maximum output power of 6mW corresponding to an overall efficiency of 6%. Previously, another 2x2 barriers HBV diode exhibited state-of-the-art performances with 9mW of output power at 250 GHz [6] corresponding to a record-breaking efficiency of 12% for triplers.

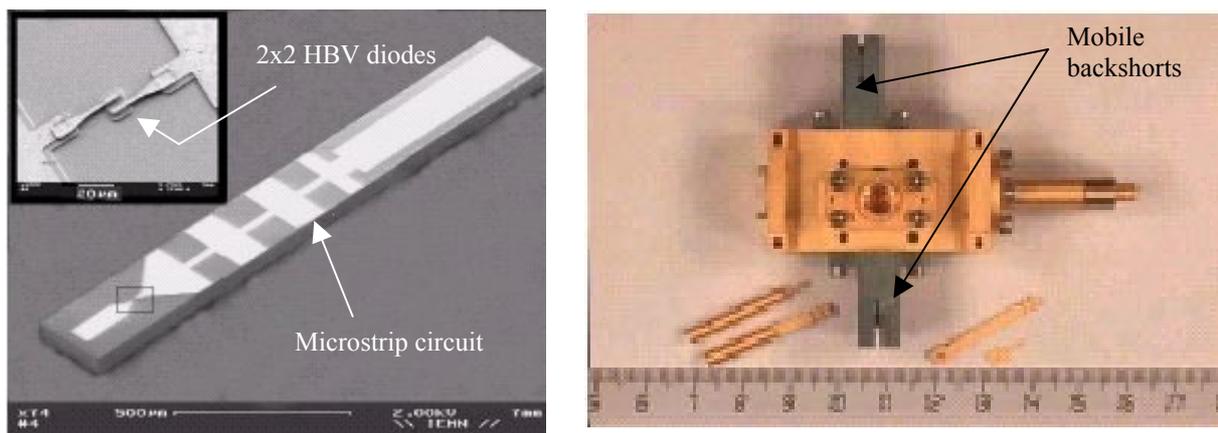


Figure 4a & 4b : schematic view of an 2x2 barriers InP-based planar HBV diode made at the IEMN and photo of the waveguide tripler block together with the mobile mechanical parts [5],[6].

Efforts are now put at the IEMN to design and build a fixed-tuned, large-bandwidth tripler in the frequency range 225-330 GHz using finline architecture [7].

Another tripler has been designed and tested by the University of Virginia[8] using the integration technique of the HBV diodes and the circuit. Measurements have shown an output power of 3.87mW and an efficiency of 4.5% at 300 GHz.

## GaAs-based planar diodes HBV triplers

Chalmers University has chosen to develop planar HBV diodes based on GaAs materials [9]. A series of 2x2 junctions is connected with a planar air-bridge in the same way (see Figure 5a) that previously described. Several architectures have been investigated :

- a cross-waveguide mount, similar to the one presented in the previous paragraph, has given 4mW of output power and 4.8% of efficiency at 246 GHz using a 2x2 GaAs barrier HBV diode,
- a finline design has been investigated (see Figure 5b) in order to avoid tunable mechanical parts and to increase the bandwidth. Performances of 0.8mW at 128 GHz was measured [10].

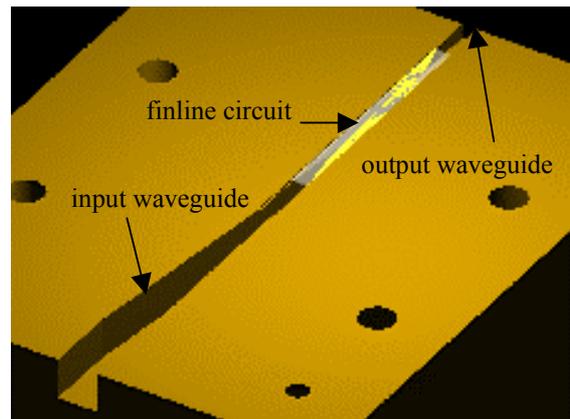
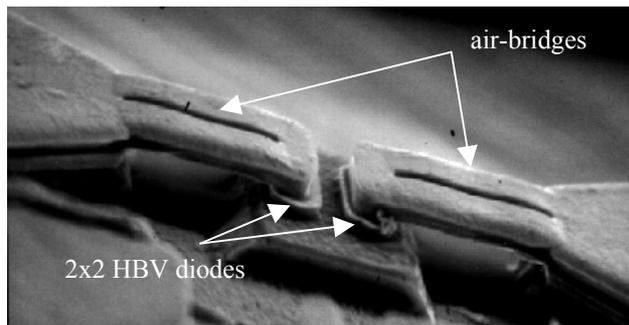


Figure 5a & 5b : photo of an 2x2 barriers GaAs-based planar HBV diode made at Chalmers and 3D view of the finline design block [10].

The Darmstadt University of Technology has obtained very recently record performances [11] at 450GHz, with a tripler using 2x2 HBV GaAs diodes mounted in a coplanar waveguide (CPW). An output power of 1 mW has been reached, corresponding to an efficiency of 1.45%.

## NLTL HBV diode triplers

Non-Linear Transmission Line (NLTL) has been investigated at Chalmers University and IEMN to increase the power handling by distributing several HBV along a propagation line.

The design presented by Chalmers is a NLTL HBV tripler using 15 HBV diodes mounted on a finline circuit (see Figure 6). This tripler exhibits 10mW peak radiated power at 130 GHz, showing 7% of efficiency [9].

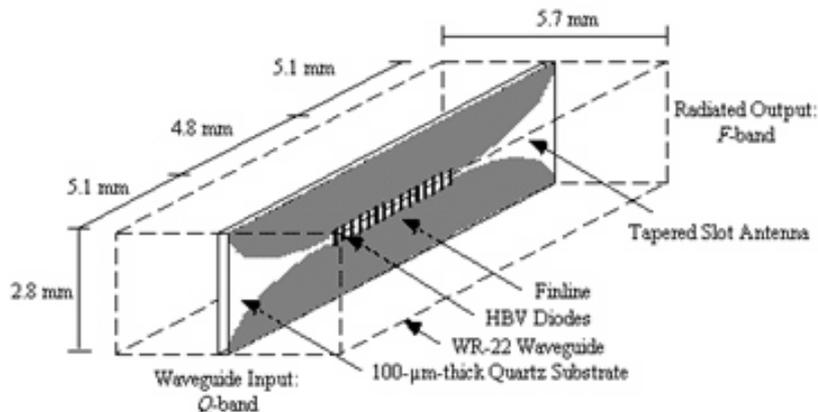


Figure 6 : Non-Linear Transmission Line HBV tripler consisting of two tapered slot antennas and a finline loaded with 15 HBVs on a 100 μm-thick quartz substrate [9].

NLTL has been also investigated by IEMN using 8 HBV diodes (shown on figure 7). This architecture uses coplanar technology for future MMIC developments [12]. On-wafer measurements have shown a maximum of 1% at 60 GHz, leading to an output power of 1 mW.

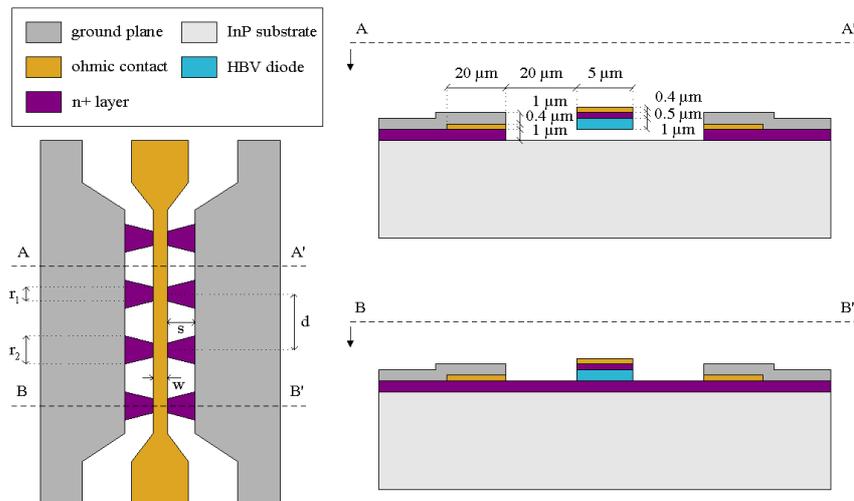


Figure 7 : Non-Linear Transmission Line HBV tripler using a coplanar design for MMIC integration [12].

Finally, the ESA TERAVISION consortium, in collaboration with the ITE (*Instytut Technologii Elektronowej*) in Warsaw (Poland), has recently investigated NLTL using 15 InP-based HBV diodes in a finline structure. No results have been published so far.

### Whisker-contacted HBV diode triplers

Designs using whisker-contacted diodes have been carried out at Chalmers University and Darmstadt University. This mounting method has been used for many years before the apparition of planar technology to contact diodes (Schottky diodes for instance). Despite many disadvantages, the goal is now to increase the power capabilities of the HBV tripler by reducing the junction temperature as much as possible. Indeed, the heating of the junction decreases the overall multiplying efficiency.

In the design presented by Chalmers University and the Rutheford Appleton Laboratory, the substrate is etched away and replaced by pure copper [9]. This offers an improved thermal heat sink. Figure 8 shows a detail of the cross-waveguide mount : the whisker is contacting a 3-barriers HBV diode. A maximum output power of 7mW was generated at 221 GHz, with a efficiency of 7.9%.

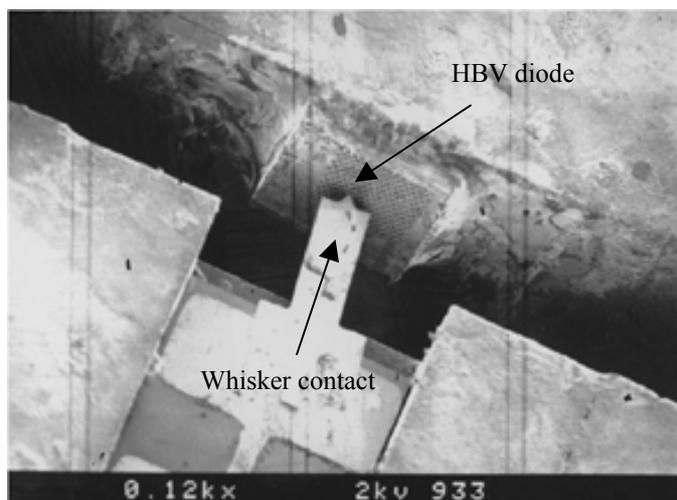


Figure 8 : HBV diodes on a copper substrate mounted in the output waveguide. The 3-barrier HBV is contacted with a whisker [9].

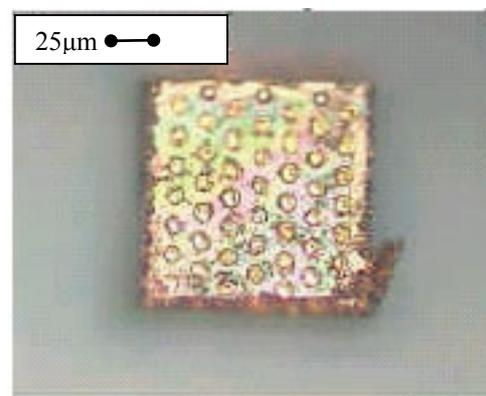


Figure 9 : whisker-contacted HBV diodes in honeycomb structure, on gold substrate [13].

The Darmstadt University has focused on the fabrication and test of whisker-contacted HBV tripler on gold substrate [13]. The gold substrate provides reduced parasitic losses and improved heat sink capabilities, which increase the efficiency of the frequency multipliers based on these devices. Preliminary measurements have shown an output power of 80  $\mu$ W and efficiency of 0.05 % at an output frequency of 450 GHz. Figure 9 shows a sample of the honeycomb structure of HBV diodes on gold substrate.

### Quasi-optical tripler developments

In quasi-optical designs, the input and output signal coupling is done quasi-optically, on the contrary of the waveguide coupling, in order to minimise the losses due to metal walls of the waveguide, using elements as filter grids, lenses and slot antennas.

The Chalmers University has designed a quasi-optical HBV diode tripler consisting of two slot antennas loaded with four planar HBV diodes and located at the focal plane of a dielectric lens [9], as shown in Figure 10. The tripler demonstrates a radiated power of 11.5mW and a conversion efficiency of 8% at 141 GHz.

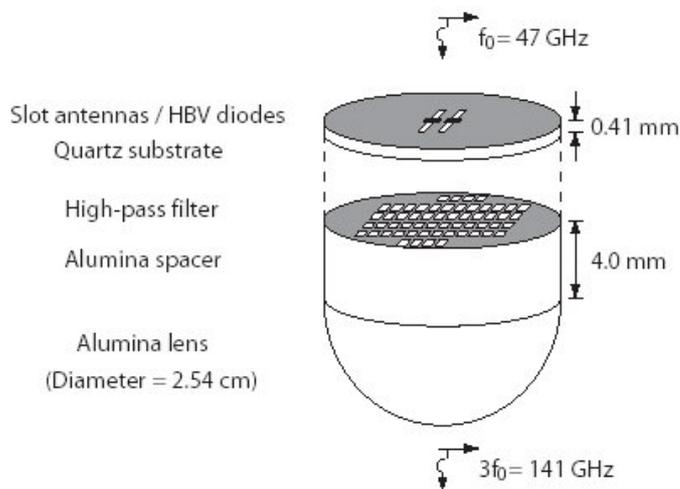


Figure 10 : quasi-optical HBV tripler developed at Chalmers University [9].

Another type of quasi-optical structure has been investigated by the University of Pavia and Darmstadt University of Technology [14] at 430 GHz. As presented in Figure 11, it consists of an open structure whose matching and filtering circuits are made with several thin slabs to couple the quasi-optical signal to an array of HBV diodes. This array generates an output beam whose frequency is multiplied. This study is still preliminary and no significant results have been obtained so far.

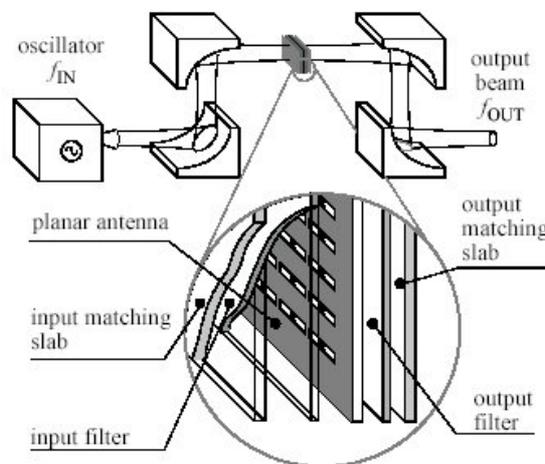


Figure 11 : quasi-optical tripler using an array of HBV diodes developed at Darmstadt [14].

Finally, the Rockwell Scientific Company in California (USA), which works closely with the University of Davis, has published recently [15] very good results at 93 GHz using a W-band quasi-optical array consisting of 196 HBV diodes mounted in a waveguide. This hybrid design, as shown on Figure 12a & 12b, uses an overmoded waveguide to couple the input and output signal to a quasi-optical array of HBV diodes. The compact 32mm<sup>2</sup> array was fabricated using 2x2 barriers per diode on a lattice –matched InP substrate.

Record Continuous Wave (CW) output power of 684mW with a peak conversion efficiency of 11.3% has been obtained at 93 GHz.

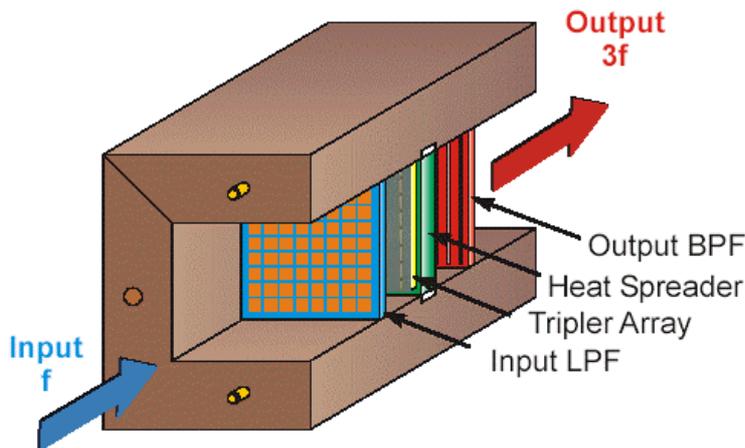


Figure 12a : Cutaway view of the quasi-optical tripler array and filter/matching slabs in a waveguide fixture [15].

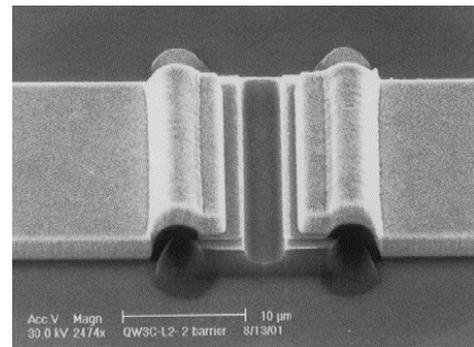


Figure 12b : SEM photograph of a 4x20µm<sup>2</sup> HBV device.

### Waveguide quintupler developments

An intent to use the fifth harmonic generated by an HBV diode has been investigated by the Chalmers University[10] and the IEMN, with the purpose to find a suitable topology for integration at frequencies above 500 GHz. Several quintupler designs have been investigated in waveguide structures. Figures 13a & 13b show several schematic views of microstrip and coplanar circuits. No significant results have been obtained.

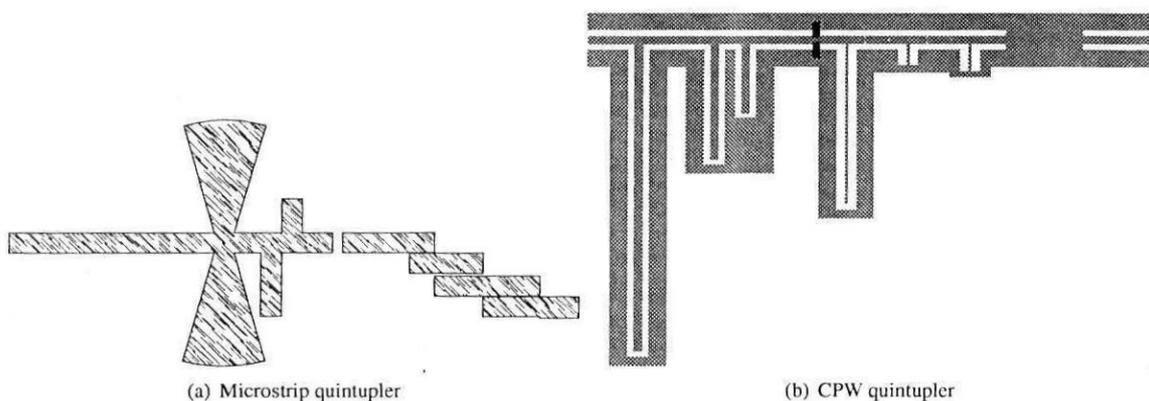


Figure 13a & 13b : schematic views of the microstrip circuits for two preliminary quintupler designs [10].

### Sideband generator developments

Finally, another type of device using HBV diodes should be mentioned. The principle is to generate a frequency tuning LO source from a fixed-frequency generator, which is specially useful at THz frequencies. Indeed, laser sources are efficient LO source at THz frequencies with an important output power (order of few milliwatts), but are fixed frequencies. In order to have a tuning source, an upconverter is used to pump the THz signal at

frequency  $f_m$  with a strong tunable microwave source (typically few GHz and several hundreds of mW) at frequency  $f_p$ . The sideband generator outputs a signal whose frequency is equal to  $2*f_p+f_m$ .

The University of Virginia has recently demonstrated this concept by designing and testing a proof-of-principle sideband generator with HBV diodes at 200 GHz [16]. A fixed-frequency signal generated at 200 GHz with 1mW of power is pumped with a microwave signal at 0.5 GHz with 250mW of input power. Measured conversion efficiencies are 10-15 dB over a 10 GHz tuning range, corresponding to an output power of 55 $\mu$ W at 201 GHz. Figure 14a & 14b shows the sideband generator block with the HBV diodes mounted on the circuit by flip-chip technique.

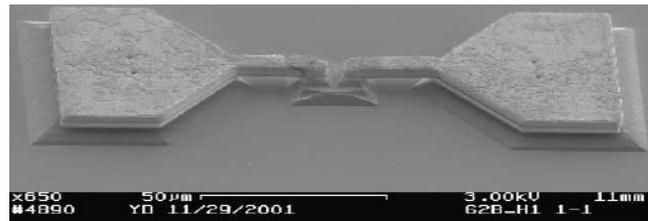
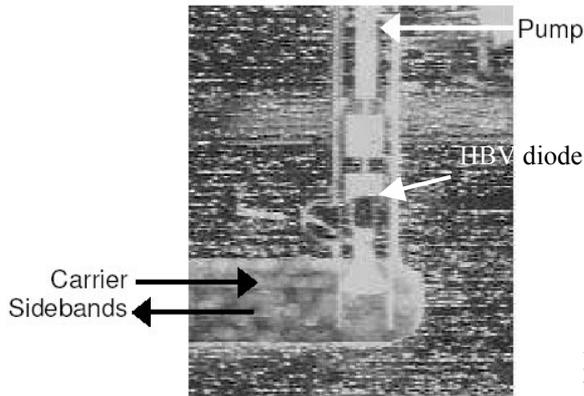


Figure 14b : SEM of a 2x2 planar HBV diode made by the University of Virginia.

Figure 14a : the photograph of the 200GHz block [16].

## Performances summary

Here is a summarising graph (see Figure 15) reviewing the state-of-the-art performances of the multipliers previously described (mainly triplers), using planar or whisker-contacted HBV diodes mounted in waveguide or quasi-optic structures.

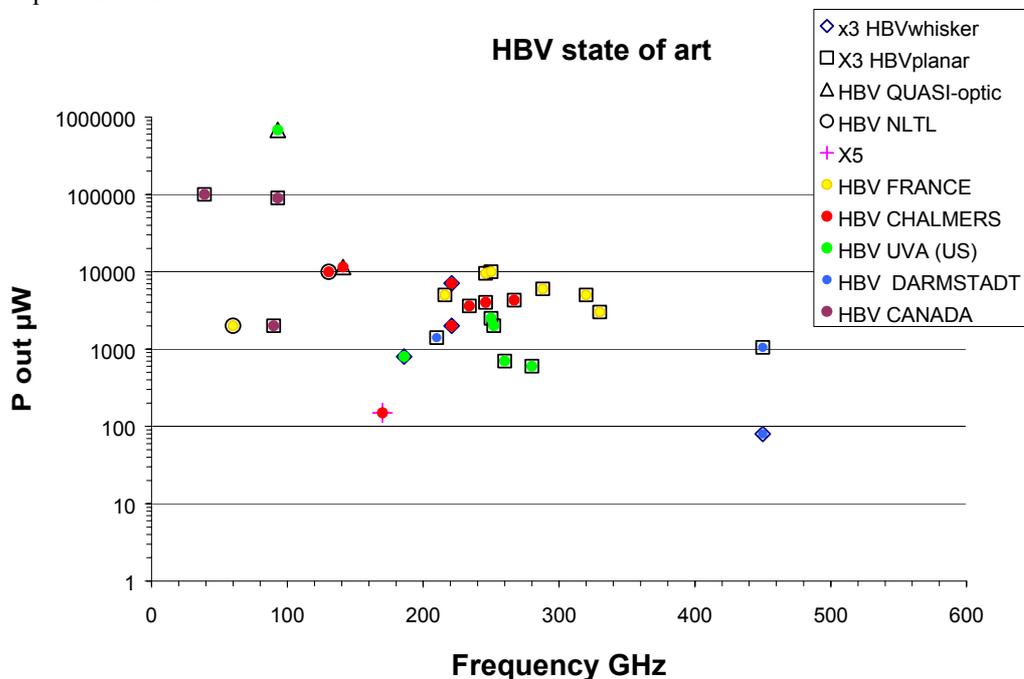


Figure 15 : table reviewing the state-of-the-art performances of HBV diode multipliers.

These results have been obtained, for the majority of the waveguide triplers, with mobile tuners in order to maximise the performances over the bandwidth. However, we believe that, if the design methods already used for Schottky varactor doublers were applied to HBV diode triplers removing the mobile tuners, its overall performances in terms of peak efficiency and instantaneous bandwidth would be greater improved.

## Conclusion

HBV diodes have demonstrated great potentiality for frequency multiplying up to the THz. An important issue for future HBV developments is the possibility to produce an important power at low frequencies using stacked devices, as it has been already demonstrated at 93 GHz [4]. This step will allow to pump higher frequencies multipliers and build tripler chains up to THz frequencies, as it is done with Schottky varactor planar doublers. Cascading several multiplier stages constraints the design to be monolithically integrated, and free of mechanical tuning parts. Self-heating of the HBV diode is an important issue to be taken into account when considering high powers, allowing to keep a good efficiency. For instance, intents by Chalmers university to design efficient heat sinks have been tried (see Figure 16), without significant results for the moment. Finally, going to the THz range implies developments in micro-machining techniques and membrane technologies.

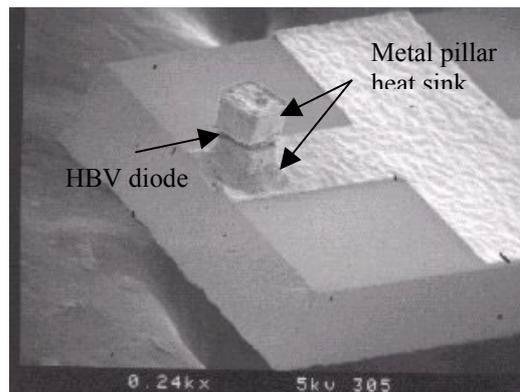


Figure 16 : pillar HBV structure soldered on a gold-on-quartz substrate. Chalmers University.

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