

# Monolithic Coplanar Transmission Lines Loaded by Heterostructure Barrier Varactors for a 60 GHz Tripler

M. Fernandez, E. Delos, X. Mélique, S. Arscott, and D. Lippens

**Abstract**—Nonlinear transmission lines (NLTLs) loaded by InP-based heterostructure barrier varactors (HBVs) have been fabricated in a monolithic coplanar technology for the first time. The devices were designed for a tripler with a 60 GHz output frequency. The single HBV diodes, fabricated in a dual barrier scheme, exhibit a capacitance ratio of 6 : 1, a normalized capacitance of  $1.4 \text{ fF}/\mu\text{m}^2$  and a voltage breakdown in excess of 10 V. Under moderate pumping (20 dBm), a tripling operation with 30% bandwidth was demonstrated with unsaturated conversion efficiency (1%) for a eight-HBV prototype.

**Index Terms**—Harmonic generation, heterostructure barrier varactor (HBV), millimeter-wave, nonlinear transmission lines.

## I. INTRODUCTION

HETEROSTRUCTURE barrier varactors (HBVs), proposed by Kollberg and Rydberg [1], have recently shown excellent performances for harmonic multiplication at millimeter wavelengths notably at 250 GHz [2]. Their key advantages are the symmetry of the capacitance–voltage characteristic and the possibility to stack the active epilayers during epitaxy to form a multi-barrier device. From a circuit point of view, this means unbiased devices, a high breakdown voltage, a low capacitance level, and the rejection of even harmonics when the devices are used for harmonic generation.

Nonlinear transmission lines (NLTLs), periodically loaded by Schottky varactor diodes, have been used for pulse generation [3] and for harmonic multiplication [4]. For the latter, the potential advantages are a broadband operation, the fact that the diodes form an integrated part of the transmission lines, the natural frequency filtering of higher-order harmonics via the band-pass character of NLTLs in case of Bragg periodicity.

The novel concepts which emerge from the use of multibarrier quantum barrier varactors for NLTLs were theoretically investigated by Shi *et al.* [5]. The idea of a fully distributed approach using a HBV-type active epilayer was also studied through numerical simulations [6]. Recently, the Chalmers group [7] has reported hybrid nonlinear transmission lines, in a

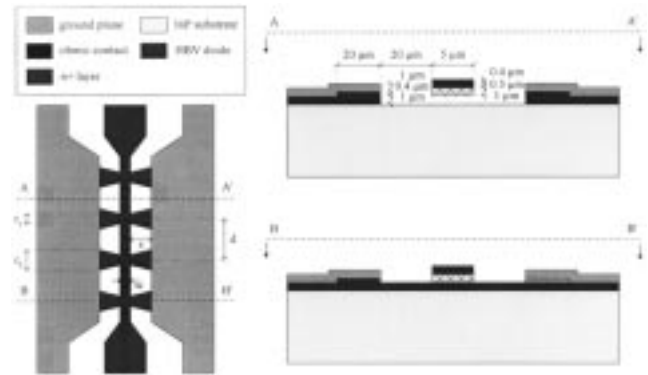


Fig. 1. Illustration of the device topology with the layout of the NLTLs and two schematic cross sections.

finline technology. In this case, the lines were loaded by GaAs discrete devices fabricated at the University of Virginia.

In this paper, we report for the first time the nonlinear characterization of nonlinear transmission lines loaded by HBVs, fabricated in a monolithic fashion. The other novelty is the use of an InP-based technology, in a coplanar configuration, for a periodically distributed tripler aimed at operating at V-band (50–75 GHz). Section II is devoted to the design and the fabrication of transmission lines. Small signal experiments by means of vectorial network analysis are reported in Section III. The results of the large signal characterization are discussed in Section IV.

## II. TRANSMISSION LINE DESIGN AND FABRICATION

Fig. 1 is a schematic of two cross sections of the coplanar waveguide together with the layout of the prototypes. The active epilayer consists of two barriers integrated in series during the epitaxial growth [2].

The topology of the transmission lines was based on nonlinear harmonic balance analysis keeping in mind the technological constraints [8]. The first result of the analysis was to point out the fact that a periodically distributed scheme is preferable to a full distributed one when harmonic generation is the targeted application [9]. The primary reason is the benefit of low passband effect resulting from the periodic arrangement of the active devices. By properly designing the Bragg cut-off frequency, a rejection of the higher order harmonics is expected. This conclusion does not hold for a fully distributed configuration which thus appears to be more suitable for pulse sharpening for which the correct transmission of the Fourier transform is imperative. Another key issue was the optimization of

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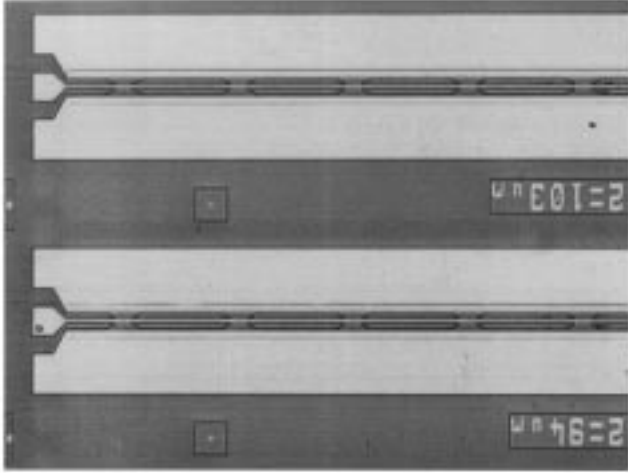


Fig. 2. Optical view of two prototypes of coplanar lines integrating HBV active material.

the series resistance of the nonlinear devices dominated by the spreading and access resistances in the buried highly doped epilayers [10]. Typically, the single diodes we fabricated have a cut-off frequency in the Terahertz range. Under these conditions, it was decided to integrate the active epitaxial material below the ridge-like central line, in a manner similar to a full distributed one. However, disconnected regions are also realized owing to free standing sections (see Fig. 1). Technologically, the prototypes were fabricated by combining highly anisotropic reactive ion etching (RIE) and isotropic wet chemical etching. For the latter, severe under-etching effects, promoted by the very high etching selectivity between InGaAs and InP, using a  $\text{H}_3\text{PO}_4$  etchant, give air gaps as shown in cross section A-A' of Fig. 1. The interconnects to the side ground lines were achieved via the  $10^{19} \text{ cm}^{-3}$  low-gap buried layer with trapezoidal-shaped patterns. The writing was implemented by electron beam and photolithography techniques.

The mask set includes four levels with several schemes by varying i) the area of the single device ( $100\text{--}250 \mu\text{m}^2$ ), ii) the number of integrated device per line (5–15), and iii) the diode inter-distance. Also, a few unloaded lines and conventional coplanar waveguides were fabricated for reference purpose. Fig. 2 is an optical view of two typical lines. The active sections are apparent with the trapezoidal shapes as seen above. Also seen is the taper section which makes a transition between the footprints for subsequent wafer probing and the nonlinear coplanar lines.

### III. SMALL SIGNAL MEASUREMENTS

The discrete devices, as well the integrated ones, were measured in a first stage by means of a network analyzer from 0.1 to 50 GHz. These measurements were conducted at 100 MHz by varying the voltage between  $-10$  and  $+10$  V. It can be noted that the symmetry in the  $C$ - $V$  characteristic was found to be excellent, a necessary feature for the even harmonic rejection. The normalized capacitance is about  $1.4 \text{ fF}/\mu\text{m}^2$  for a dual barrier scheme. A high capacitance contrast between the zero bias  $C_{j0}$  and the saturation value  $C_{sat}$  of 6:1 was also measured with

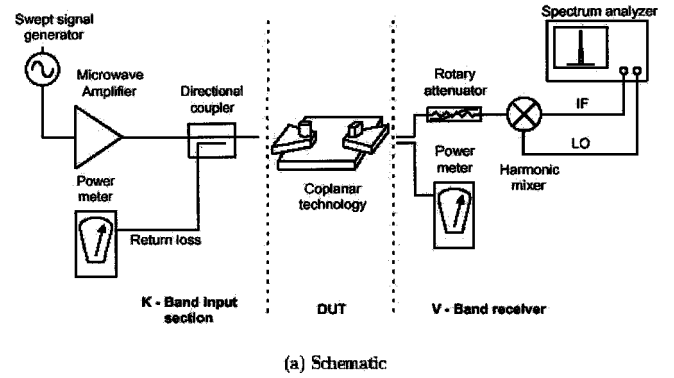


Fig. 3. Schematic of the experimental setup implemented for the large signal measurements.

a steep voltage-dependence. The  $I$ - $V$  characteristics exhibit an anti-symmetry with a large voltage range over which the leakage current is extremely low ( $10 \text{ A}/\text{cm}^2$ ), the breakdown due to impact ionization occurring for about 12 V.

For the integrated scheme, the unbiased devices show relatively high return loss. This is primarily due to the low characteristic impedance ( $\sim 30 \Omega$ ) of the loaded line under small signal conditions with respect to the  $50 \Omega$  source reference. The impedance of the unloaded lines is  $\sim 80 \Omega$ . The  $S_{21}$  frequency dependence exhibits a band pass filter characteristic as expected with a small-signal cut-off around 50 GHz.

### IV. LARGE SIGNAL rf MEASUREMENTS

In the following, we will focus on the rf assessment of  $200 \mu\text{m}^2$ -diameter eight-diode prototype with a slot of  $20 \mu\text{m}$  whereas the strip width was  $5 \mu\text{m}$ . Fig. 3 depicts the experimental set-up used for these large signal experiments. For the pump source, we used a swept frequency generator between 200 MHz and 50 GHz. This primary signal served to feed a medium power microwave amplifier which operates between 2 and 20 GHz with a maximum delivered power of 24 dBm. Above 20 GHz a roll-off of the delivered power can be measured so that only moderate power measurements can be conducted. The analysis, in the bandwidth of major concern, was set by the output waveguide in WR 15 (V band 50–75 GHz). Additional spectrum analysis was performed at Q-band (second harmonic) and W-band (fourth and fifth harmonics). Owing to the excellent symmetry of the  $C$ - $V$  characteristic, the even harmonics were efficiently rejected. The fifth harmonic rejection through Bragg reflections depends on the nonlinearity of the diodes which is high for the present batch. For the power measurements, we used as for the input section a calibrated bolometer head.

We first checked that the line was properly designed for a  $3 \times 20$  GHz operation. This was demonstrated with several transmission lines with a diode inter-distance between 260 and  $290 \mu\text{m}$ . A maximum in efficiency was achieved around 20 GHz. Fig. 4 illustrates the spectrum analysis recorded in this case. The up-converted signal peak is well centered at 60 GHz.

The bandwidth was only estimated at moderate power because of the limited power source over the full band (17–25

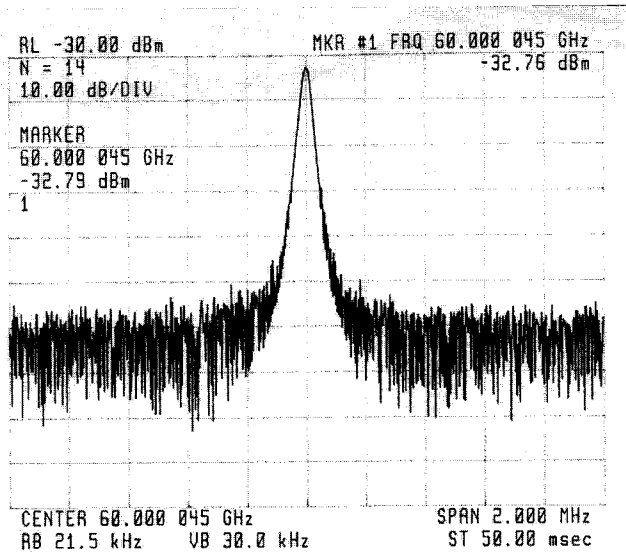


Fig. 4. Spectrum analysis of an eight-diode device.

GHz). It was found that the device operates readily between 17 GHz and 23 GHz. For the up-converted frequency window, this gives a value around 30% in agreement with the numerical simulations. The theoretical frequency dependence exhibits a gaussian shape similar to that shown with NLTLs loaded by Schottky diodes. Experimentally, the variations of the output power versus frequency show some ripple due to reflections at the output.

In a second stage, we tested the efficiency of the tripler as a function of the number of cascaded diodes. Theoretically it can be demonstrated that there exists an optimum number of devices. Intrinsically, such a maximum can be understood in the soliton-like model as it was proposed over the past for Schottky barrier devices [11]. For the present non rectifying device, similar solitary waves can be used. The losses due to the distributed sections and the series resistance lowers this optimum number of diodes per line. Experimentally, the eight-diode chip gave the best results.

The last series of measurement concerned the up-conversion efficiency at 20 GHz. The study of the efficiency versus the input power did not show saturation effects. The highest conversion efficiency achieved in these moderate power experiments was 1% for 20 dBm of available power source. Such a finding is in agreement with harmonic balance (HB) simulations including the overall losses. Under 1 W pumping power, the expected efficiency calculated with HB code is around 10%. In terms of voltage across the diode, it can be shown that this 20 dBm pumping condition does not permit to pump the diodes over the full voltage range, typically a 20 V peak-to-peak value for proper operation. We expect further improvements in terms of conversion efficiency for harder pumping conditions (larger nonlinearity and better large signal matching). The transmis-

sion line and diode losses which are determinant in these distributed approaches [8] could be further optimized by thicker metal overlays, finger-shaped metallic contact pads, and air-bridge technologies. Transfer substrate techniques onto quartz, recently demonstrated in our group [12] for discrete devices, could be interesting for this distributed technology.

## V. CONCLUSION

A monolithic prototype of a nonlinear transmission line loaded by high-quality heterostructure barrier varactors was fabricated and rf tested for the first time to our knowledge. The preliminary experimental results are in agreement with the small and large signal analysis, with respect to the number of devices, unwanted frequency rejection, and overall efficiency. Further improvements through harder pumping conditions and optimized topology can be expected with 10% efficiency under 1 W pumping.

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