A 141-GHz Quasi-Optical HBV Diode Frequency Tripler

Stein Hollung, Jan Stake, Lars Dillner and Erik Kollberg

Chalmers University of Technology
Department of Microelectronics ED
Microwave Electronics Laboratory
SE-41296 Göteborg, Sweden

Abstract — A 141-GHz quasi-optical heterostructure barrier varactor (HBV) diode frequency tripler is presented. The tripler consists of two slot antennas loaded with HBV diodes and located at the focal plane of a dielectric lens. A quasi-optical high-pass filter is used at the output to improve the conversion efficiency and act as a tuning element for the slot antennas. The tripler demonstrates an effectively isotropic radiated power (EIRP) of 2.24 W at 141 GHz with an input power of 143 mW. The corresponding radiated power is 11.5 mW and the tripler conversion efficiency is about 8%.

I. Introduction

The increasing demand for inexpensive sources for millimeter- and submillimeter-wave applications has motivated the use of solid-state devices such as varactor diodes to generate higher harmonics from less expensive low-frequency sources. Quasi-optical grid multipliers are capable of producing high output power [1]-[3], but are often inefficient due to large diffraction losses and require bulky dielectric lenses and powerful sources. Several waveguide mounted tripler circuits have been reported with good efficiency [4]-[6], but machining of these waveguide circuits can be both complicated and expensive. An integrated planar antenna multiplier can provide an inexpensive, less complicated and efficient transmitter front-end. While a variety of millimeter-wave and submillimeter-wave receivers with double-slot antennas fabricated on dielectric lenses have been presented to date [7]-[11], few transmitters have been reported.

Here we present a quasi-optical frequency tripler with four heterostructure barrier varactor (HBV) diodes soldered across two slot antennas and located at the focal plane of a dielectric lens as shown in Fig. 1. The slot antennas are fed from a WR-22 waveguide connected to a Gunn oscillator. A quasi-optical high-pass filter is used to tune the slot impedance and increase the conversion efficiency. The symmetric capacitance-voltage and asymmetric current-voltage characteristics of the HBV diodes only allows odd harmonics of the applied signal to be generated, and thus simplifies the frequency tripler design [12]-[13].

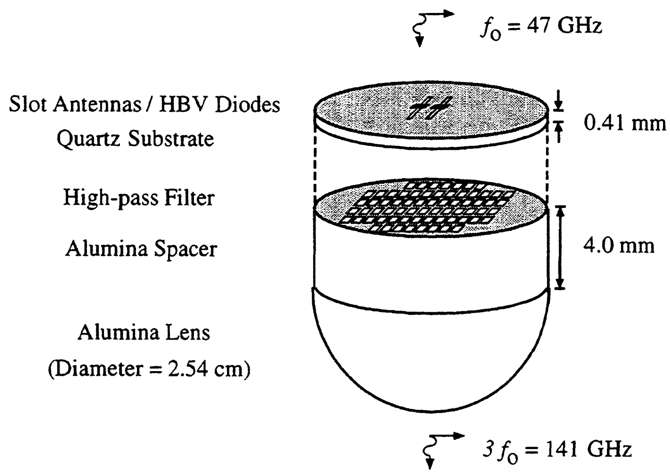


Fig.1. The quasi-optical tripler circuit consisting of two slot antennas loaded with four HBV diodes on a quartz substrate, a quasi-optical high-pass filter, an alumina spacer and a 2.54-cm diameter spherical alumina lens.

II. DESIGN

The planar four-barrier GaAs/$Al_{0.7}$GaAs HBV diodes (UVA-NRL-1174-17) [5] used for this circuit has a device area of 57 μm^2. The optimum embedding impedances at the fundamental (47 GHz) and third harmonic (141 GHz) frequency of two of these devices in parallel were found from harmonic balance simulations [13] to be 16+j126Ω and 22+j53Ω, respectively. Two diodes are soldered in parallel across each of the two slot antennas to lower the required input impedance of the slots and increase the power handling capability of the tripler.

The input impedance of the slot antennas on a layer structure as shown in Fig. 1 and with a CPW feed, was simulated using HP Momentum as shown in Fig. 2. The optimal embedding impedances of the HBV diodes at the fundamental and third harmonic frequency can be seen to match the input impedance of a short slot antenna. This property was first recognized and used by Arcioni *et al.* [3] for a quasi-optical HBV grid tripler design. The fabricated slot antennas are 1.36 mm long, 0.07 mm wide, spaced by 0.387 mm, and fabricated on a quartz substrate with permittivity ε_r = 4.6. A quasi-optical high-pass filter is used to tune the impedance of the slot antennas as well as improve the input coupling efficiency. The high-pass filter consists of an array of 0.4-mm square slots with a period of 0.45 mm. A 0.41-mm-thick stack of quartz substrates separates the filter and slot antennas. The slots were fabricated on a quartz substrate, to achieve sufficiently high input impedance. A 4-mm-thick alumina spacer is used to locate the high-pass filter at the hyperhemispherical point of a 2.54-mm-diameter alumina lens with permittivity

$\varepsilon_r = 9.8$. The slots are thus located at a distance 0.41 mm behind the hyperhemispherical extension length resulting in a slightly higher directivity [9].

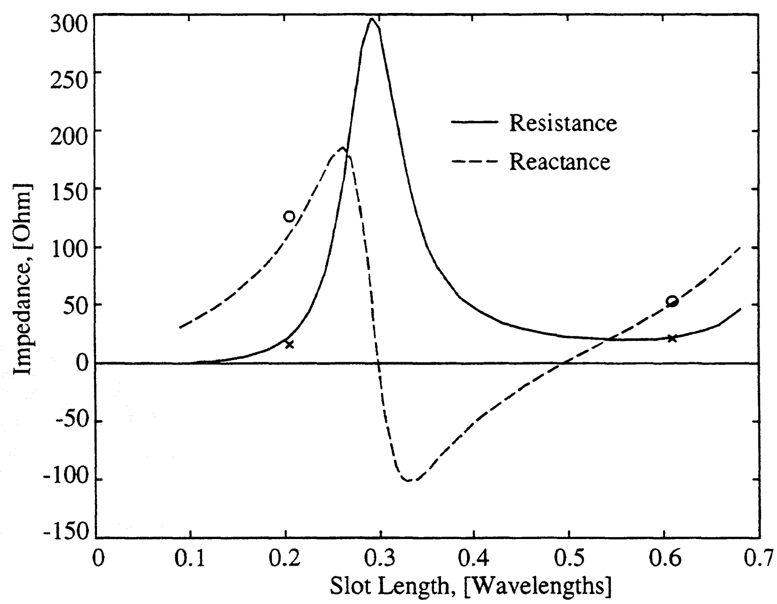
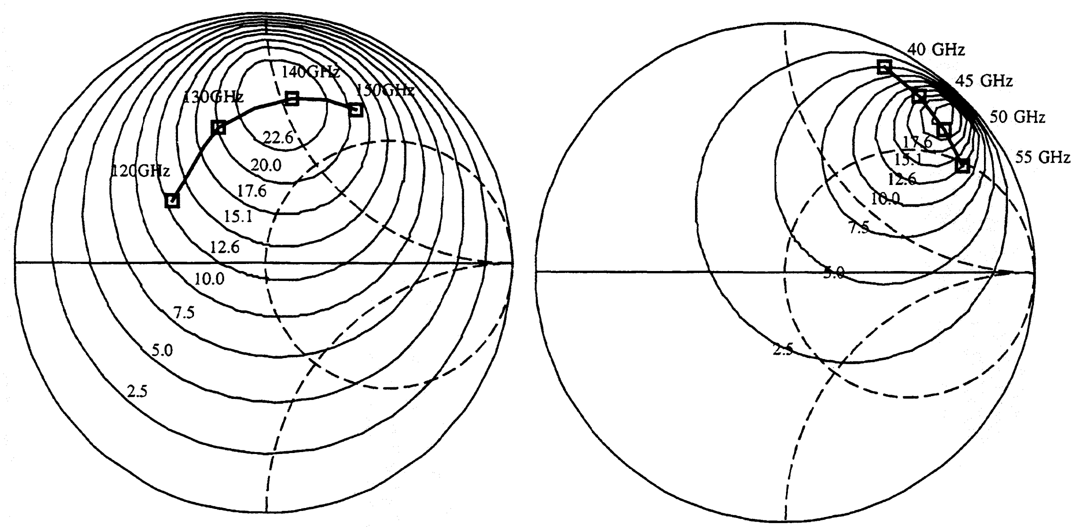


Fig. 2. Simulated input impedance of a slot antenna as a function of slot length. The slot width is 5 % of the slot length. The simulated optimum embedding impedances of two HBV diodes in parallel at the fundamental and the third harmonic are also indicated for a pump frequency of 47 GHz.

The conversion efficiency of the tripler as a function of embedding impedance at the fundamental and third harmonic frequency was simulated using an harmonic balance model of the HBV diodes [13] as shown in Fig. 3. The maximum conversion efficiency of the tripler is 25.1% with a pump power of 100 mW at 47 GHz. Included are also the simulated input impedances of the slot antennas as a function of frequency around the fundamental and third harmonic frequency. Notice that the input match at the fundamental frequency limits the bandwidth of the tripler. An estimated 3-dB bandwidth of about 10% can be seen from the figure.



(a) (b)

Fig. 3. Simulated conversion efficiency of an HBV tripler as a function of embedding impedance at the a) fundamental frequency and b) the third harmonic for a pump frequency of 47 GHz. The maximum efficiency is 25.1% and each contour describes a 10 % reduction in efficiency. The simulated input impedance of a slot antenna as a function of frequency is also shown.

III. EXPERIMENTS

The open end of a WR-22 waveguide with an *E*- and *H*-plane tuner connected to a Gunn-diode oscillator was used to feed the slot antennas as shown in Fig. 4. While the input impedance calculations assume a plane-wave feed, the slot antennas are located at the plane of the open-ended waveguide during the experiments to minimize spillover loss. The *E-H* tuner is then used to optimize the input coupling to the slots. An *F*-band horn antenna located in the far-field of the lens and connected to an Anritsu power sensor is used to measure the radiated power at the third harmonic. The tripler demonstrates an effectively isotropic radiated power (EIRP) of 2.24 W at 141 GHz for an input power of 143 mW as shown in Fig. 5.

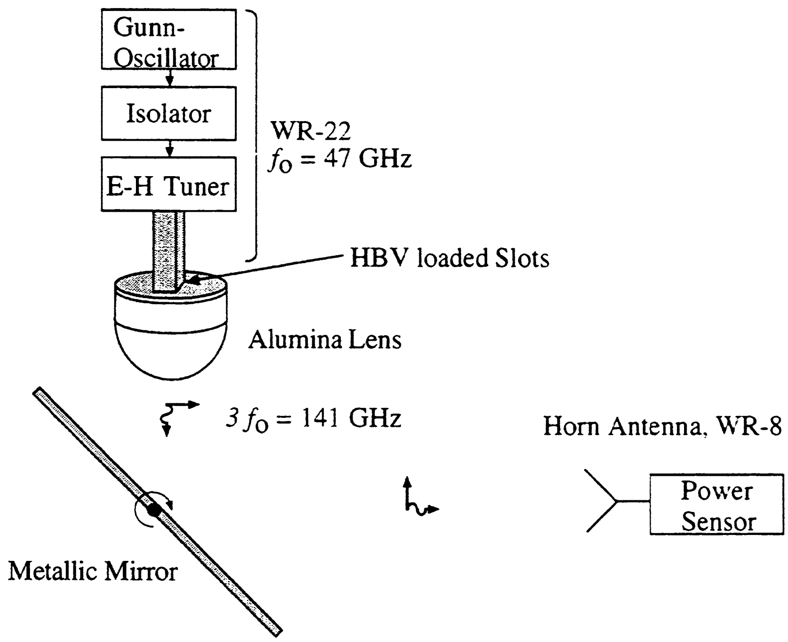


Fig. 4. Experimental set-up for the quasi-optical tripler measurements.

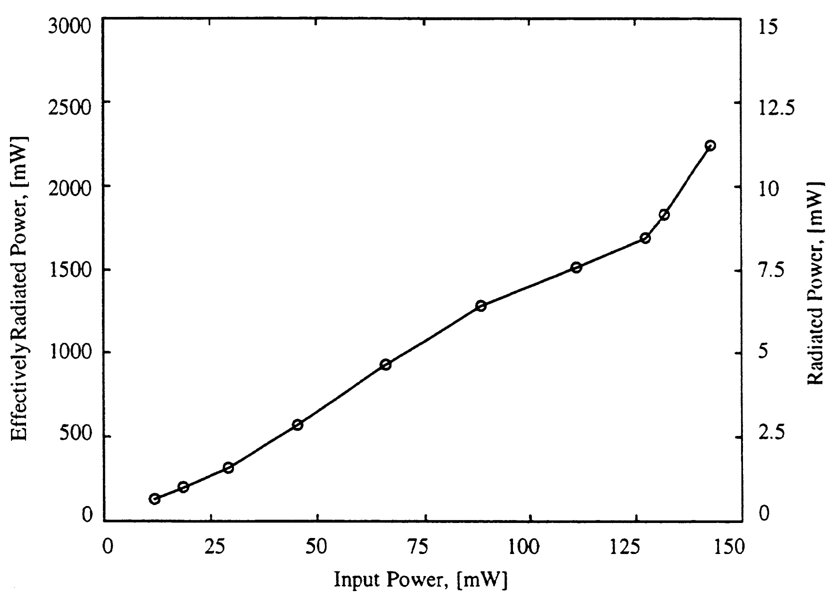
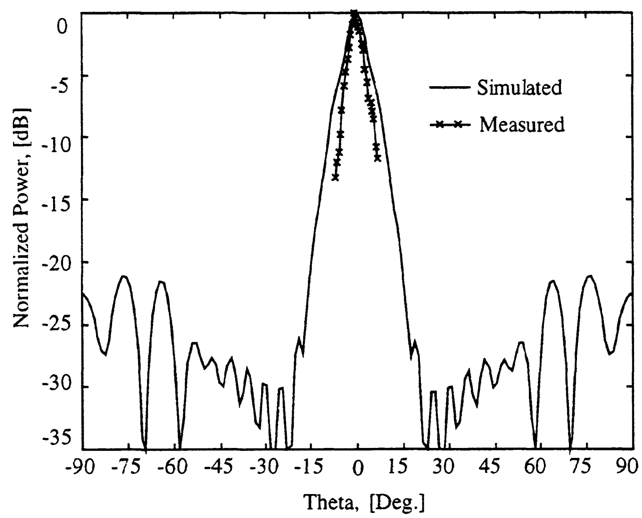
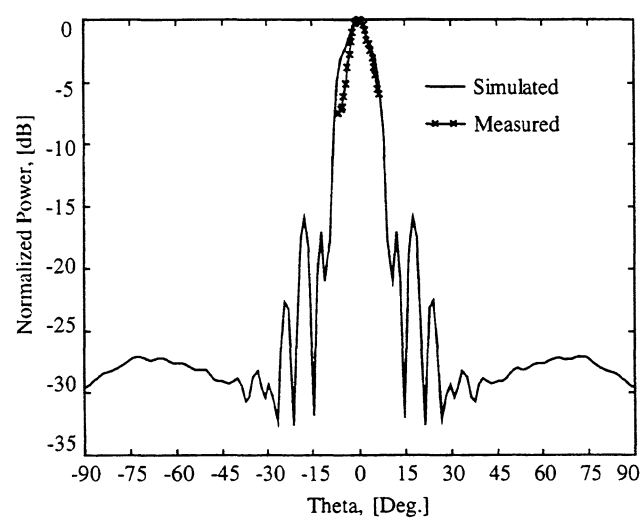


Fig. 5. Effectively isotropic radiated power (EIRP) and estimated radiated power from the tripler at 141 GHz.

Using the simulated radiation patterns of the double-slot antenna into the dielectric lens from Momentum simulations, the radiation patterns from the lens was calculated using a ray tracing technique [11]. Both measured and simulated *E*- and *H*-plane radiation patterns for the lens at 141 GHz are shown in Fig. 6.



(a)



(b)

Fig. 6. Measured and simulated (a) *E*-plane and (b) *H*-plane radiation pattern for the tripler at 141 GHz.

The measured cross-polarized signal was below the detector sensitivity level, or more than 10 dB relative to the co-polarized on-axis power level, for all angles in both planes. The measured 3-dB beamwidth in the *E*- and *H*-plane are 6 and 7 degrees, respectively. From the measured radiation patterns, a directivity of 22.9 dB can be estimated for the slot-fed lens.

A radiated output power of about 11.5 mW, with a corresponding conversion loss of 10.9 dB can be estimated. The conversion loss is defined as the available power from the input waveguide at the fundamental frequency to the power radiated from the lens at the third harmonic. A slightly better conversion loss of 10.5 dB was measured with 110-mW input power as shown in Fig. 7.

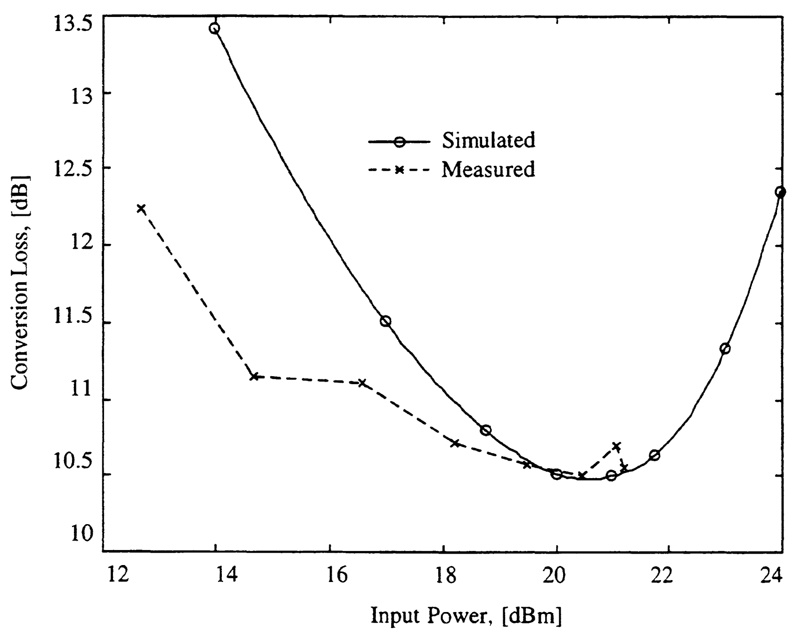


Fig. 7. Measured and simulated conversion loss for the tripler circuit. The conversion loss is defined as the available power at the fundamental from the waveguide to the power radiated from the lens at the third harmonic.

The conversion loss of the four HBV diodes as a function of pump power was calculated using the device model presented in [13]. The calculated conversion loss of the four HBV diodes is 6 dB (25.1% efficiency) for a pump power of 100 mW at 47 GHz assuming optimum embedding impedances and room temperature operation. An estimated loss of 1.0 dB at the input and 3.5 dB at the output was added to the diode conversion loss to approximate the measured conversion loss. The output loss can be due to reflection losses at the lens surface (0.5 dB was estimated from ray tracing), losses in the dielectric and high-pass filter, misalignment of the receive horn, mirror, lens and slot antennas, overestimated gain of the receive horn, and mismatch of the diodes at the output. No significant power was measured radiating from the substrate edges due to substrate modes. The input loss is due to coupling loss from the waveguide to the slots as well as mismatch losses of the diodes at the fundamental frequency. At the fundamental, an effectively isotropic radiated power of 1.4 W was measured. If a directivity of 17 dB is assumed for the slot-fed lens at 47 GHz, a radiated power of 28 mW from the lens at the fundamental frequency can be estimated.

IV. ACKNOWLEDGMENT

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