ABSTRACT A W band (75 – 110 GHz) communication link using monolithic integrated single-diode circuits is proposed. The circuits are based on GaAs Schottky diodes with cutoff frequencies around 1.5 THz integrated with on-chip folded slot antennas and near-field 3D printed dielectric lenses. The total chip area is $1.4 \times 3.5 \, \text{mm}^2$. The receiver module shows a peak isotropic voltage sensitivity of 12260 mV/mW at 94 GHz, with a noise equivalent power of 12 pW/$\sqrt{\text{Hz}}$. These results include the slot antenna and a 3 mm radius 3D printed lens. The transmitter acts as a free-space W band signal generator using the non-linear properties of the diode for frequency multiplication. Multiplication orders up to $\times 15$ are tested for input powers of 10 mW. The generated power is measured by a horn antenna placed at a distance of 100 mm from the transmitter and a 2D map for the frequency range 90 – 100 GHz and multiplication orders between $\times 2$...$\times 15$ is presented. The two circuits are used to demonstrate W band communication links using 1 kHz amplitude modulated input signals with carriers at 6 GHz, X band and in the Ku band. Voltages of hundreds of mV are detected for a distance of 150 mm between transmitter and receiver circuits and tens of mV at 600 mm. The proposed approach can be used as a low cost and low complexity alternative for point-to-point high-speed wireless communications.

INDEX TERMS Gallium arsenide, millimeter wave communications, MMICs, rectennas, Schottky diodes.

I. INTRODUCTION

In the last decades, the solid-state diode technology has registered great progress such as the reduction of the device feature size down to nanometer scale, with an increase of the operating frequency up to hundreds of gigahertz, enabled by the use of high-quality semiconductor materials [1]. The diodes can be monolithically integrated with passive components which reduces parasitics and improves device repeatability. High performance power detectors, mixers and frequency multipliers were developed in the millimeter (mm) wave and sub-mm wave frequency ranges [2] using this approach.

The monolithic integration of an antenna offers additional benefits such as compact front-ends, removal of the requirement of an interconnecting reference impedance of 50 Ohm in the design and elimination of parasitic elements (important in the mm-wave frequency range) [3], [4], [5]. GaAs direct detection (video) receivers were reported in [6] for 45 GHz...
for the integration of a Schottky diode (SD) with a micromachined Yagi-Uda antenna and in [7] for the integration of SD with membrane supported double folded slot antenna at 38 GHz operating frequency. A micromachined 38 GHz quasi-optical mixer was presented in [8]. The symmetrical radiation pattern of the micromachined double folded slot antenna is used to bring at the SD terminals both radiofrequency and local oscillator signals. More recently, a monolithic integrated antenna and SD multiplier for free space W band (75 – 110 GHz) power generation was reported in [9]. In these papers the whole front-end was simulated and designed using 3D electromagnetic (EM) analysis and linear/nonlinear circuit techniques. The experimental characterization was based on the concept of isotropic power which includes the integrated antenna performances. In [6] the “isotropic voltage sensitivity” $\beta_{V,\text{iso}}$ was defined and a value of 6000 mV/mW was measured at 45 GHz. In [8] the “isotropic conversion losses” parameter was used and a value of 15 dB was measured at 38 GHz. In [9] the “isotropic conversion loses” parameter was measured for multiplication orders of $x_2, x_3, x_4$ and $x_5$ and values of 11.5...26.4 dB were reported.

The current paper presents frontend circuits that monolithically integrate on the same GaAs substrate a slot antenna, a coplanar waveguide (CPW) matching section, one GaAs Schottky diode and a CPW low-pass filter. This circuit is used for free space amplitude modulated (AM) W band signal generation using frequency multiplication as well as W band signal reception and demodulation. W band communication links with input signals starting from 6 GHz, X band and Ku band are successfully demonstrated. These bands have an abundance of commercial circuits available for the generation and AM modulation of RF signals. One possible application is the high-speed data transfer in the 90 – 100 GHz for point-to-point communications, wireless sensor networks, multi-gigabit per second streaming etc.

Section II describes the design and fabrication of the frontend circuits for the transmitter and receiver MMICs. Simulated and measured results for the antenna radiation pattern are presented. The measured results for the receiver module are presented in Section III, including isotropic voltage sensitivity, isotropic tangential signal sensitivity and noise equivalent power. Section IV presents the transmitter module measured results and emitted power in the 90 – 100 GHz frequency range for up to 15 times order of multiplication. The measured results for the W band communication link follow in Section V. An amplitude modulated signal feeds the input of the transmitter and it is received and demodulated. The tested input frequencies are in the 6 GHz range, in the X band (8 – 12 GHz) and in the Ku band (12 – 18 GHz) and the transmission distance is tested up to hundreds of millimeters.

II. DESCRIPTION OF THE MMIC BLOCKS

The frontend circuit monolithically integrates a slot antenna, a CPW matching network, one GaAs Schottky diode and a CPW stepped impedance low-pass filter (Fig.1) connected to an external port. The Schottky diodes developed in the current work have an optimized layer structure composed of a 0.2 $\mu$m thick Schottky layer (doping concentration $1 \times 10^{17}$ cm$^{-3}$), a 0.5 $\mu$m thick Ohmic layer (doping concentration $1 \times 10^{18}$ cm$^{-3}$) and a 2 $\mu$m thick low temperature GaAs layer grown on a 400 $\mu$m semi-insulating GaAs (100) substrate. The Schottky contact has an area of $\sim 1 \mu$m$^2$ and is placed in the center of the first mesa (area of $10 \times 10 \mu$m$^2$) which is, in turn, configured in the center of the second mesa (area of $23 \times 23 \mu$m$^2$). The distance between the Schottky contact and the surrounding Ohmic contact is between 7 – 10 $\mu$m. A suspended bridge is used to contact the device (Fig. 1 inset).

![FIGURE 1. SEM images of fabricated receiver and multiplier circuits with detail of the schottky contact.](image1)

![FIGURE 2. Circuit schematic developed in AWR Microwave Office.](image2)

The design started with the circuit from Fig. 2, developed in AWR Microwave Office using coplanar waveguide transmission lines (electromagnetic quasi-static model). This circuit was used for the initial optimization of the layout dimensions. The diode was modeled with the small circuit equivalent circuit (parallel connection of junction capacitance, Cj, and equivalent resistance, Rj) in series with the series resistance, Rs) [10].
Some small signal parameters were estimated from experimental I/V characteristics (saturation current 10…20 fA, ideality factor 1.2…1.35, series resistance 30-50 ohm) with the zero-voltage capacitance of about 2 fF [9]. The Schottky diode cutoff frequency is around 1.5 THz, more than 10 times that of the upper limit of the W band (75 – 110 GHz).

The low pass filter has a high impedance (Zhigh – Wh, Lh, Gh) low impedance (Zlow – Wl, Ll, Gl) topology and a cutoff frequency of about 45 GHz. The filter was designed and a standalone device was fabricated and tested. The comparison between measured and simulated S parameters is presented in Fig. 3 (the layout parameters definition and the final values are also included).

A 3D full wave EM model was developed for the conductor-backed (i.e., backside metallization) folded slot antenna in CST Studio Suite and used for antenna design through parametric optimization with the goals antenna matching and broadside antenna directivity. In this approach several antenna layout parameters are varied and the designer chooses the best trade-off between the two goals. It should be noted that the common design techniques [11] are inaccurate for a conductor-backed folded slot antenna placed on a substrate with a thickness of about half wavelength for semi-insulating GaAs in the W-band. To exemplify the approach Fig. 4 (a) presents the frequency dependence of the antenna reflection coefficient (left) and the antenna directivity (right) for different values of the antenna strip length parameter (inset in Fig. 4 (b)). The value length = 0.5 mm was selected for the standalone antenna fabrication. The other parameters are the strip width (0.12 mm) and the gap space (0.05 mm). The CPW feed has a gap of 0.05 mm and a signal line of 0.1 mm. The comparison between simulated and measured results (Fig. 4 (b)) validated the design technique.

The transmitter integrates a frequency multiplier and an antenna. The layout was designed for optimum power transfer from the diode equivalent impedance at the output frequency to the on-chip antenna [10]. Even if a 0 V external DC bias voltage is applied to the Schottky diode, it will be “self-biased” in current by the rectified microwave input power. The targeted input frequency for the multiplier is between 6 GHz and 17 GHz and the circuit connected to the second SD terminal (Fig. 1) has a negligible reactance. A view of the 3D full wave EM model developed in CST is presented in Fig. 5 (a). The diode, modeled with its small signal equivalent circuit, is connected at the discrete port, and the junction resistance is the internal impedance of the excitation source. The discrete port feature of CST is used. The simulated radiated power is shown in Fig. 5 (b) as a function of frequency. The simulated current density distribution at 94 GHz is presented in Fig. 5 (c) and illustrates the proper operation of the antenna, matching network and low pass filter.

The receiver integrates an antenna and a detection block (rectenna). The design goal of maximum power transfer in the 90 – 100 GHz frequency range between the signal received by the antenna from free space and the diode was achieved using gamma shaped stubs in the matching network (Fig. 1). A 100 μA DC bias current corresponding to a junction resistance of about 300 Ohm was considered in the design. This bias is applied through the receiver external port.

In order to increase the antenna’s gain by about 6 dB and concentrate the radiation in a single direction, a hemispherical dielectric lens was designed by means of full wave EM analysis [12]. The relative permittivity of the 3D printed dielectric was estimated around 2.75 for PLA (polylactic acid) filament [13]. The hemispherical lens has a radius of 3 mm and a 1.5 mm extension and is placed at a distance of 2.75 mm from the antenna. The simulated 3D radiated power density distribution of the multiplier at a 1 m reference distance is shown in Fig. 6 (a) for 94 GHz. The corresponding directivity
is 6.7 dBi. The simulated 3D radiated power density distribution after adding the dielectric lens is shown in Fig. 6 (b) and the simulated directivity is 12.8 dBi.

The lens was fabricated using a FDM (Fused Deposition Modeling) 3D printing process and mainstream PLA (polylactic acid) filament, that is a low-cost alternative to other approaches (like silicon lenses).

The 3 mm radius hemispheres were 3D printed with 100% infill and 100 µm layer thickness, ensuring good material deposition uniformity. The support was printed separately and the lens was glued in place (Fig. 7). The 3D printed structure was manually aligned with the theoretical radiation center of the folded slot antenna and fixed to the support PCB with double sided adhesive tape.

For the fabrication of the frontend circuits (transmitter and receiver MMICs) the main steps of the fabrication process are described in [9]. The area of the receiver and multiplier chips is $1.4 \times 3.5 \text{ mm}^2$. The chips were placed on printed circuit boards and wire bonded to a 50 Ohm CPW transmission line (Fig. 7). For the receiver, a U.FL Hirose coaxial connector is used to collect the demodulated signal. For the transmitter circuit a SMA Amphenol (extended range) coaxial connector is used to feed the multiplier.

The radiation pattern of the receiver module including the 3D printed lens and a video amplifier was measured using the experimental setup described in Section III. The setup included a goniometric holder, which allows for the continuous rotation of the receiver with $-90 \ldots +90$ degrees in the horizontal plane. The receiver is then rotated in the holder with $90^\circ$ around its main radiation direction, thus enabling the acquisition of the radiation characteristic of both 2D orthogonal planes. The E plane (in this case, the plane of symmetry of the layout) and H plane measured results are compared with the simulated ones in Fig.8.
Thanks to the remarkable advances of low-cost commercially available FDM 3D printers, EM focusing performances similar to SLS (Selective Laser Sintering) were obtained [12]. Using the two orthogonal radiation characteristics −3 dB beamwidths, a gain of about 12 dBi is estimated at 94 GHz.

III. RECEIVER MODULE MEASUREMENTS

The experimental setup used for the receiver module measurement is presented in Fig. 9. The emitting horn antenna and receiver module are placed on a slider stage, in test fixtures ensuring the alignment of the horn and dielectric lens antenna. Wideband absorbent material was placed around the setup. The signal generated by the programmable signal generator (PSG Agilent E8257C) feeds a W band standard horn antenna (Millitech SGH110) and illuminates the receiver from a distance of 100 mm (Fig. 9 (b)). The signal is 100 % modulated in amplitude with a square wave signal with a frequency of 1 kHz.

The demodulated signal is extracted with a coaxial cable and amplified by a video amplifier. The amplifier is based on the INA818 Precision Instrumentation Amplifier from Texas Instruments (35-μV Offset, 8-nV/√Hz Noise, Low-Power). It includes two INA818 and a OPA191 (Low-Power, Precision), the latter used to eliminate the input DC voltage offset caused by the DC bias of the Schottky diode. Fig. 10 shows a photo of the fabricated circuit with SMD components. A U.FL type connector was chosen for the input and a SMA connector was used for the output.

The circuit was tested using a function generator at the input and an oscilloscope at the output. The measured voltage gain was 576, the 3 dB bandwidth was over 100 kHz, with the lower frequency limit of 0.5 Hz. Because the circuit power supply consists of two CR2032 batteries, the output peak-to-peak amplitude is limited to about 5.8 V. The circuit includes a network to bias the Schottky diode with a DC current of about 100 μA using a series resistor connected at the amplifier positive DC supply. The output signal of the amplifier is displayed on an oscilloscope (Tektronix DPO2024).

Since the receiver MMIC circuit combines the function of an antenna and a detector (a rectenna), the isotropic voltage sensitivity ($\beta_{V,iso}$) is used to characterize the circuit performance. The $\beta_{V,iso}$ is defined as the ratio between the amplitude of the detected signal and the incident isotropic power $P_{iso}$ calculated with (1) at the antenna reference plane.

$$P_{iso} = P_{gen}G_{horn} \left( \frac{\lambda}{4\pi d} \right)^2$$

where: $\lambda$ is the free-space wavelength; $d$ is the distance between the horn antenna and the receiver plane; $G_{horn}$ is the gain of the horn antenna and $P_{gen}$ is the power level at the output of the cable that feeds the horn antenna.
The measured results are presented in Fig. 11 (a). The maximum value of 12260 mV/mW was obtained at 94 GHz (after removing the video amplifier voltage gain). This value is several times higher than those reported in [6], but the bandwidth is narrower. The level of the input power was limited by the value of output voltage amplitude saturation of the video amplifier (thus the $\beta_{V,iso}$ below 92 GHz is small, but not zero).

A second parameter is the “isotropic tangential signal sensitivity” $T_{SS, iso}$. It was measured using a square wave amplitude modulated signal attenuated to the limit of detection [16].

The value of the $T_{SS, iso}$ is equal to the isotropic power level which corresponds to these conditions. The measured values are shown in Fig. 11 (b). The minimum value of $-49$ dBm at 94 GHz is better than those reported in [6]. The noise equivalent power ($NEP$) of the receiver can be calculated with (2). At 94 GHz a value of about $12 \text{ pW}/\sqrt{\text{Hz}}$ is calculated and is comparable with commercial diodes from OMMIC and Virginia Diodes Inc. [1].

$$T_{SS, iso} = 2.5 \cdot NEP \cdot \sqrt{\Delta f}$$

where $NEP$ is the noise equivalent power of the receiver and $\Delta f$ is the frequency band of the video amplifier.

IV. TRANSMITTER MODULE MEASUREMENTS

The experimental setup used for the characterization of the transmitter (multiplier) circuit is presented in Fig. 12. The transmitter is fed from a signal generator (PSG Agilent E8257C) with frequencies between 6 – 50 GHz (corresponding to multiplication orders between $\times 2 \ldots \times 15$) with a measured input power around 10 dBm. The extended range SMA connector (Amphenol) of the multiplier module proved to be low loss even at these high frequencies (measured losses $< 1$ dB up to 50 GHz). A bias Tee with a short-circuit at the DC port was used to bias the diode at 0 V. The emitted wave was received by a W band horn antenna (Millitech SGH110) placed at a distance of 100 mm and connected to a spectrum analyzer (Anritsu MS2668C) equipped with a W band subharmonic mixer.

A color map of the power received in the 90 – 100 GHz frequency range by a horn antenna placed at a distance of 100 mm from the multiplier module for multiplication orders between $\times 2 \ldots \times 15$.

V. COMMUNICATION LINK DEMONSTRATION

The main goal of this paper is to demonstrate through experiments the implementation of a wireless communication link in the W band that uses similar low complexity MMIC blocks for both frequency multiplication and signal reception and demodulation. The main characterization results are presented in Sections III and IV for the 90–100 GHz frequency range.

Even though the emitted power is maximum for $\times 2$ and $\times 3$ multiplication, this work addresses $\times 15$ (input frequency
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FIGURE 14. Measurement setup for the characterization of the W band communication link (a) General schematic; (b) Photo detail of the setup.

FIGURE 15. Demodulated signal for a 1 kHz AM modulated 8.25 GHz input signal and a distance of 150 mm between transmitter and receiver modules.

FIGURE 16. Demodulated signal amplitudes for: (a) input signals in the 6 GHz band; (b) input signals in the X band; (c) input signals in the Ku band for a distance of 150 mm between the multiplier and receiver modules.

range 6 – 6.7 GHz), ×11 (input frequency range 8.2 – 9.1 GHz) and ×6 (input frequency range 15 – 16.6 GHz) multiplication orders. These bands have an abundance of commercial circuits available for the generation and amplitude modulation of RF signals at a relative low cost.

The experimental setup for the characterization of the W band communication link is shown in Fig. 14. The transmitter and receiver circuits are connected as described in Sections III and IV. The microwave signal at the input of the transmitter is 100% amplitude modulated with a square wave signal with a frequency of 1 kHz. After frequency multiplication and a propagation distance of 150 mm it is received, demodulated and displayed on an oscilloscope (Tektronix DPO2024). An example of the demodulated signal is shown in Fig. 15.

The measured amplitudes for the demodulated signals are presented in Fig.16 (a) for input signals in the 6 GHz band, Fig.16 (b) for input signals in the X band and Fig.16 (c) for input signals in the Ku band. The ripples in the frequency responses are mainly due to the standing waves created in the measurement environment by multiple reflections between the equipment from the experimental setup. Because of these standing waves it is not possible to accurately predict the responses from Fig.16 using the measurements from Section III and IV. Also, it should be noted that, for the frequencies in the 6 GHz and 8 GHz ranges, the transmitted signals can have outputs from different orders of multiplication in the receiver bandwidth.

Signals can be detected at distances up to 600 mm where amplitudes of 50 – 60 mV were measured for input
frequencies in the 6 GHz and 8 GHz ranges and 10 mW powers at the input of the multiplier DUT. This was the maximum distance where the alignment between the receiver and transmitter modules could be ensured with the available setup.

VI. CONCLUSION
The paper presented frontend circuits that monolithically integrate a slot antenna with a GaAs Schottky diode, a coplanar waveguide low-pass filter and a matching network on the same GaAs substrate. First, the design and fabrication results for the receiver and transmitter modules were briefly described. In order to increase the antenna gain, a hemispherical dielectric lens was designed, fabricated and tested. The simulated results of the 2D radiation pattern are in fair agreement with the experimental results indicating a gain of about 12 dBi at 94 GHz.

Next, the measured results for the receiver module were presented, including isotropic voltage sensitivity, isotropic tangential signal sensitivity and noise equivalent power. A low-noise video amplifier with a gain of 576, a 3 dB bandwidth of over 100 kHz and lower frequency limit of 0.5 Hz was used for measurements. The best results were obtained at 94 GHz (12260 mV/mW isotropic voltage sensitivity and −49 dBm isotropic tangential sensitivity). The noise equivalent power for the receiver diode was extracted as 12 pW/\sqrt{Hz}. These results include the antenna performances and are comparable to current commercial W band detector diodes.

The measured results for the transmitter (multiplier) module for multiplication orders between ×2...×15 were presented in the next section. The emitted power has maximum values at 93 GHz for different multiplication orders.

Finally, communication links in the W band with input signals starting from 6 GHz, X band and Ku band were successfully demonstrated. These bands have an abundance of commercial circuits available for the generation and amplitude modulation of RF signals at a relative low cost. The transmission distance was tested up to 600 mm, which is remarkable considering the input power at the multiplier input was in the range of 10 mW.

The proposed approach can be used for high-speed data transfer in the 90 – 100 GHz frequency range enabling multi-gigabit per second wireless links.

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