A D-band Frequency-Doubling Distributed Amplifier Through Monolithic Integration of SiC SIW and GaN HEMTs

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***Abstract*—This is the first report of a distributed amplifier (DA) realized through monolithic integration of transistors with a substrate-integrated waveguide (SIW). The DA uses a stepped-impedance microstrip line as the input divider like in conventional DAs, but uses a low-loss, high-power-capacity SIW as the output combiner. The input signal is distributed to four GaN high-electron mobility transistors (HEMTs) evenly in magnitude but with the phase successively delayed by 90° at the fundamental frequency. The HEMTs are separated by a half wavelength at the second harmonic frequency in the SIW, so that their outputs are combined coherently at the SIW output. To overcome the limited speed of the GaN HEMTs, they are driven nonlinearly to generate second harmonics, and their fundamental outputs are suppressed with the SIW acting as a high-pass filter. The measured characteristics of the DA agree with that simulated at the small-signal level, but exceeds that simulated at the large-signal level. For example, under an input of 68 GHz and 10 dBm, the output at 136 GHz is 24-dB above the fundamental. Under an input of 68 GHz and 20 dBm, the output at 136 GHz is 14 dBm, with a conversion loss of 6 dB and a power consumption of 882 mW. This proof-of-principle demonstration opens the path to improving the gain, power and efficiency of DAs with higher-performance transistors and drive circuits. Although the demonstration is through monolithic integration, the approach is applicable to heterogeneous integration with the SIW and transistors fabricated on separate chips.**

Keywords—distributed amplifier, frequency doubler, millimeter wave, MMIC, power combining, substrate integrated waveguide

I. INTRODUCTION

With the bandwidths of 6G wireless communications and next-generation automobile radars extending above 110 GHz, high-frequency, high-power transmitters are needed [1], [2]. However, the output power of monolithic microwave integrated circuits (MMICs) above 110 GHz is presently limited to the order of 30 dBm [3] by the speed of transistors and the loss of power combiners. This paper proposes to overcome these limits by a frequency-doubling input divider and a substrate-integrated waveguide (SIW) output combiner. As a proof of principle, the frequency doubler is based on GaN high-electron mobility transistors (HEMTs) while the SIW is based on a SiC substrate. GaN HEMTs have relatively high power capacity but relatively low speed. SiC is an excellent SIW material because it offers high dielectric constant for compact size, high electrical resistivity for low loss, high breakdown strength for high power capacity, strong mechanical toughness for robust fabrication, high thermal conductivity for heat dissipation, but low loss tangent and matching thermal expansion coefficient [4], [5]. High-power GaN HEMTs are typically fabricated on SiC, so that GaN HEMTs can be monolithically integrated on an SiC SIW without additional process complexity.

Frequency multiplication can be used to boost the input drive at high frequencies [1], [2]. GaN frequency multipliers have been demonstrated below 110 GHz, including a doubler with 5-dB conversion loss and 10-dBm output at 77 GHz [6], and another doubler with 3.8-dB conversion loss and 13.8-dBm output at 100 GHz [7]. We believe ours is the first report of a GaN frequency doubler above 110 GHz.

Conventionally, power combiners are based on coplanar or microstrip transmission lines, which suffer from high loss, significant crosstalk, and limited power capacity at frequencies above 110 GHz. By contrast, SIWs have low loss, minimum crosstalk, and high power capacity [8], [9]. Normally, SIWs are implemented at the board level. However, above 110 GHz, SiC SIWs are small enough to be integrated monolithically on chip [4], [5]. Further, the SIW is intrinsically a high-pass filter to help suppress the fundamental leakage. We believe this is also the first report of a SIW-based MMIC. The monolithic integration of GaN HEMT frequency doublers with an SIW power combiner in a distributed amplifier is described below.

II. DESIGN AND FABRICATION

Fig. 1 shows the layout of the distributed amplifier based on an SiC SIW in which the propagating wave is bounded by two rows of through-substrate vias (TSVs) connecting the top and bottom ground planes. The two TSV rows are 480-μm apart to cut off waves below 100 GHz. The SiC substrate is 50-μm thick. Embedded along the middle of the SIW are four hot TSVs isolated from the ground planes and separated by $\lambda_{SIW}/2$ from each other, where λ_{SIW} is the wavelength in the SIW at the output frequency. Each hot TSV is driven by a HEMT, making it resemble a voltage probe in a waveguide but driven in reverse so that it acts as an antenna to radiate waves into the SIW. The input signal is distributed to each

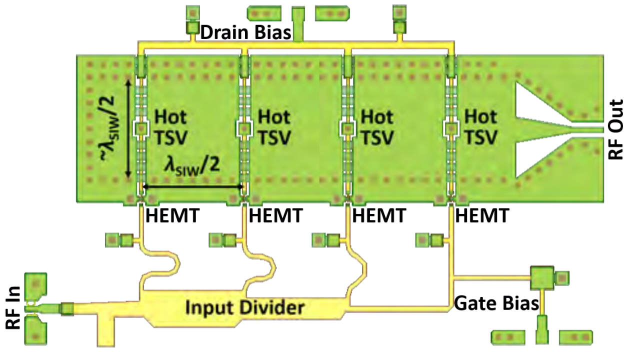
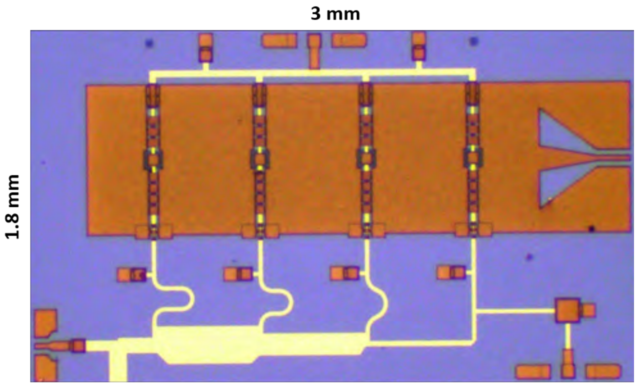
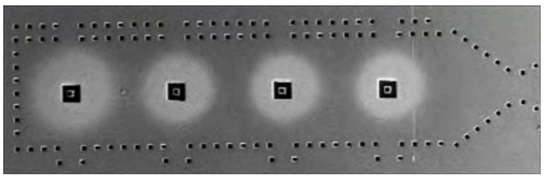


Fig. 1. Layout of the distributed amplifier.



(a)



(b)

Fig. 2. (a) Optical micrograph of the front side and (b) SEM micrograph of the backside of a distributed-amplifier chip.

HEMT evenly in magnitude but with 90° successive phase delays at the fundamental frequency through a stepped impedance (width) microstrip line. The right end of the SIW is transitioned to a coplanar line to facilitate wafer probing. The left end of the SIW is shorted by another row of TSVs $\lambda_{SIW}/4$ from the nearest hot TSV, so that the backscattered wave is reflected and added constructively to the forward propagating wave.

The distributed amplifier is fabricated by HRL Laboratories using its T3 40-nm GaN-on-SiC HEMT technology with cutoff frequencies f_T = 200 GHz and f_{MAX} = 400 GHz [10]. According to the HRL-supplied HEMT model, under a gate bias of V_{GG} = −1.5 V, a drain bias of V_{DD} = 12 V, and an input of 10 dBm at 68 GHz, each 2 × 25 μm HEMT can output 6.4 dBm at 136 GHz to a hot TSV with an impedance of 29 + j51 Ω. Because HRL does not support hot TSVs, the HRL-fabricated chips are postprocessed at Cornell University to create hot TSVs by using a focused Ga ion beam to etch away 80 × 80 μm^2 of back metal around the four TSVs in the middle of the SIW. Fig. 2 shows the front and back micrographs of the 3 × 1.8 mm^2 distributed-amplifier chip.

III. Measurement and Results

Scattering (S) parameters are measured from 1 to 220 GHz in a single sweep using an Anritsu ME7838G vector network analyzer with two Anritsu MA25400A frequency extenders, and two MPI TITAN T220A-GSG050 220-GHz probes [5], [11]. Output spectra are measured from 1 to 220 GHz with the input frequency extender replaced by an Eravant SBP-5037033522-VFVF-S1 50–70-GHz, 22-dBm power amplifier and the input probe replaced by an MPI TITAN T67A-GSG0075 67-GHz probe. A Rohde & Schwarz NRP110T 110-GHz power sensor is used to calibrate the input power. Output powers are measured at 136 GHz with the output frequency extender replaced by an Erickson PM5B power meter (Fig. 3). All measurements are calibrated to the probe tips. Simulations are performed by ADS and HFSS using HRL models.

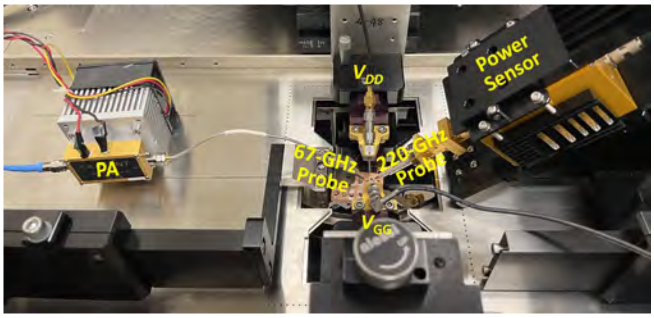


Fig. 3. Power measurement setup.

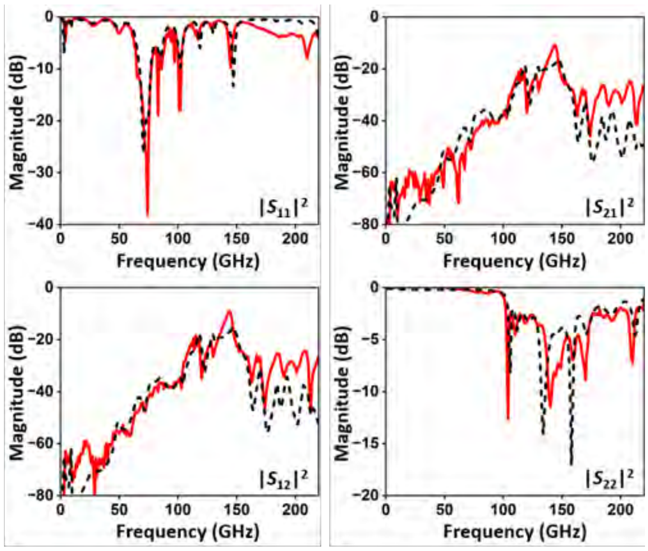


Fig. 4. Measured (solid) vs. simulated (dash) S parameters of the distributed amplifier. V_{GG} = −1.5 V; V_{DD} = 12 V.

Fig. 4 shows that the S parameters measured on the distributed amplifier agree with that simulated across the ultrawide bandwidth of 220 GHz. As designed, $|S_{11}|^2 < -20$ dB from 68 to 75 GHz and $|S_{22}|^2 > -1$ dB below 100 GHz.

Fig. 5 shows the ultra-wideband 220 GHz output spectrum measured on a thru line or a distributed amplifier under an input of 68 GHz. The thru is a 150-μm coplanar line on an MPI TCS-050-100-W impedance standard substrate, which is used to verify the linearity of the input signal and receiver. It can be seen that under an input power of 0 dBm, the output harmonics at 34, 136, and 204 GHz are 33, 53, and 60 dBc, respectively. With the input increased to 10 dBm, the fundamental output increases by 10.2 dB as expected. In contrast, under the same input of 10 dBm, the output of the distributed amplifier decreases by 45 dB at 68 GHz but increases by 28 dB at 136 GHz. Meanwhile, there is no change

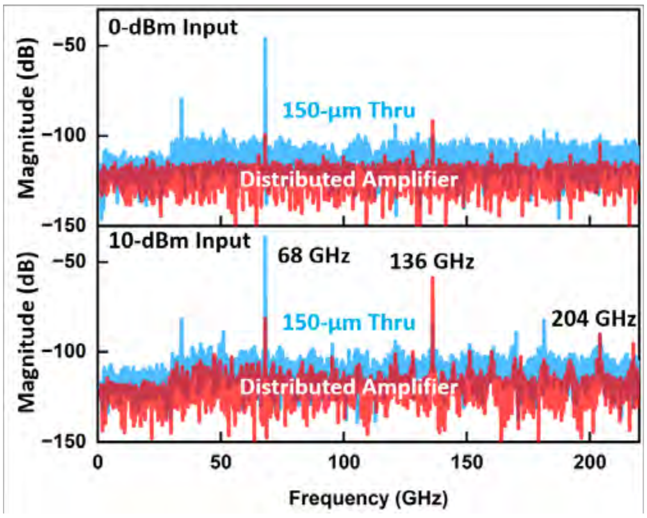


Fig. 5. Out spectrum measured on a thru line or a distributed amplifier under an input of 68 GHz and 0 dBm (top) or 10 dBm (bottom). $V_{GG} = -1.5$ V; $V_{DD} = 12$ V.

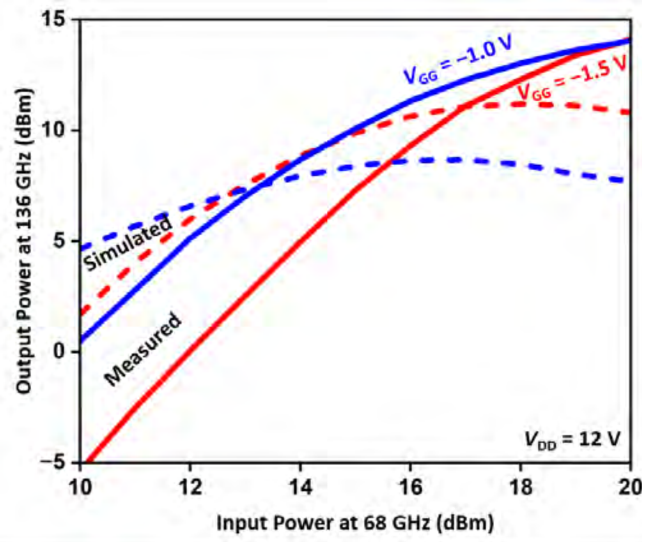


Fig. 6. Measured (solid) vs. simulated (dash) gain-compression characteristics of the distributed amplifier.

at 204 GHz. Thus, compared to the magnitude at 136 GHz, the magnitudes at 68 and 204 GHz are lower by 24 and 32 dB, respectively.

Fig 6 shows the measured gain-compression characteristics of the distributed amplifier is rather different from that simulated, indicating that unlike the small-signal model, the large-signal model does not accurately capture harmonic generation. In the future, the large-signal model can be improved by using our newly established ultra-wideband capability for large-signal characterization of a 68-GHz transistor up to its third harmonics. Presently, the measured characteristics indicate that, with V_{GG} increased from −1.5 to −1.0 V, the linear gain increases but the saturated power remains the same. Under an input of 68 GHz and 20 dBm, the output power at 136 GHz is 14 dBm (conversion loss = 6 dB) and the DC power consumption is 882 mW. The output power of the present frequency doubler at 136 GHz is comparable to that of [7] at 100 GHz, but significantly higher than that of [6] at 77 GHz. With the high power capacity of the SIW, the output power of the distributed amplifier can be increased above 30 dBm by replacing discrete HEMTs with multistage HEMT amplifiers.

IV. Conslusion

This work demonstrates a novel power-combining concept through monolithic integration of transistors with an SIW. We believe this is the first report of an SIW-based MMIC and a D-band frequency doubler in the GaN technology. Taking advantage of the lower loss and higher power capacity of the SIW than that of microstrip or coplanar transmission lines, much higher output power can be achieved by replacing the present HEMTs with higher-performance transistors and drive circuits. Although the demonstration is through monolithic integration, the approach is applicable to heterogeneous integration with the SIW and transistors fabricated on separate chips.

Acknowledgment

We thank Y. Tang of the Department of Physics, Cornell University, for his technical assistance in ion milling. This work is supported in part by the US National Science Foundation (NSF) under Grants ECCS-2117305, ECCS-2122323, and ECCS-2132329, the US Department of Defense under the State of the Art Radio Frequency Gallium Nitride program, as well as the Semiconductor Research Corporation and the US Defense Advanced Research Projects Agency through the Joint University Microelectronics Program. This work was performed in part at the Cornell Center for Materials Research which is supported by NSF through Grant DMR-1719875.

References

[1] U. Gustavsson *et al.*, "Implementation challenges and opportunities in beyond-5G and 6G communication," *IEEE J. Microw.*, vol. 1, no. 1, pp. 86–100, Jan. 2021.

[2] W. Hong *et al.*, "The role of millimeter-wave technologies in 5G/6G wireless communications," *IEEE J. Microw.*, vol. 1, no. 1, pp. 101–122, Jan. 2021.

[3] Hua Wang *et al,* "Power amplifiers performance survey 2000-present," [Online]. Available: https://ideas.ethz.ch/Surveys/pa-survey.html.

[4] M. J. Asadi *et al,* "Substrate-integrated waveguides for monolithic integrated circuits above 110 GHz," in *IEEE MTT-S Int. Microw. Symp. Dig.,* Atlanta, GA, Jun. 2021, pp. 669−672.

[5] L. Li *et al.,* "Single-sweep vs. banded characterizations of a D-band ultra-low-loss SiC substrate integrated waveguide," in *ARFTG Microw. Meas. Conf.,* Denver, CO, USA, Jun. 2022.

[6] I. Kallfass *et al.*, "A single-chip 77 GHz heterodyne receiver MMIC in100 nm AlGaN/GaN HEMT technology," in *IEEE MTT-S Int. Microw. Symp. Dig.,* Jun. 2011, pp. 1–4.

[7] T. Sonnenberg, S. Verploegh, M. Pinto, and Z. Popović, "W-band GaN HEMT frequency multipliers," *IEEE Trans. Microw. Theory Techn.*, DOI: 10.1109/TMTT.2023.3253185.

[8] T. Yoneyama and S. Nishida, "Nonradiative dielectric waveguide for millimeter-wave integrated circuits," *IEEE Trans. Microw. Theory Techn.,* vol. 29, no. 11, pp. 1188–1192, Nov. 1981.

[9] D. Deslandes and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microw. Wireless Compon. Lett.*, vol. 11, no. 2, pp. 68–70, Feb. 2001.

[10] K. Shinohara *et al.,* "Scaling of GaN HEMTs and Schottky diodes for submillimeter-wave MMIC applications," *IEEE Trans. Electron Devices,* vol. 60, no. 10, pp. 2982–2996, Oct. 2013.

[11] T. Li, L. Li, and J. C. M. Hwang, "Validity of room-temperature calibration for on-wafer measurements up to 220 GHz, 125 °C, and 48 h," in *ARFTG Microw. Meas. Conf.,* San Diego, CA, Jun. 2023.