A Tunable 220 GHz Comb Generator Realized With an Ultrawideband Mixer in an InP HBT Technology

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***Abstract*— We present a novel approach to millimeter-wave electrical comb generators with frequency-adjustable tone spacing and a tunable RF center frequency. We upconvert the spectrum of a series of repetitive pulses with an ultrawideband (UWB) mixer to demonstrate a stable electrical comb from 140 GHz to 220 GHz, with 500 MHz and 2 GHz frequency spacings. This upconverted comb can be used as a phase reference at millimeter-wave frequencies once an accurate characterization of the phase of its spectrum is available.**

***Index Terms*— Comb generator, millimeter wave, monolithic microwave integrated circuit (MMIC), on-wafer calibration, ultrawideband (UWB) mixer.**

I. Introduction

SEMICONDUCTOR foundries have developed technologies that now operate above 100 GHz. Although scattering parameters and scalar measurements can be performed up to 1.1 THz with waveguide extenders [1], the characterization of active devices with multitone signals and absolute phase calibration is currently limited to 67 GHz with commercial phase references and to 110 GHz when using a photodiode calibrated with an electrooptic sampling (EOS) system [2].

Phase references are obtained by generating a broadband electrical comb with a known phase of its spectrum. They provide a phase relationship between each harmonic tone of the nonlinear signals that are characterized with large signal network analyzers. The frequency spacing of the electrical comb must fall on the frequency grid that is used to characterize the signal. The power of the spectrum of the comb must exceed the noise floor of the nonlinear network analyzer, usually around −100 dBm. Several millimeter-wave comb generators based on nonlinear transmission lines [4], [5], [6], [7], step recovery diodes [8], [9], [10], Josephson junctions [11], and split-signal pulse generators [12], [13], [14] have been reported. A millimeter waveband-limited comb generator has also been published [15]. Although a broadband comb generator exhibiting a minimum bandwidth of 110 GHz has been recently demonstrated [14], there is still a need for phase references to characterize, for instance, band-limited modulated signals above 100 GHz.

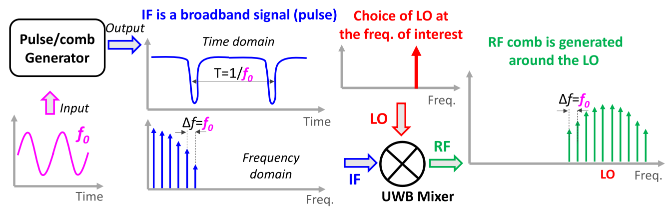

Fig. 1. New millimeter-wave electrical comb generator realized with a broadband electrical comb (series of repetitive pulses) and a UWB mixer. In this letter, we characterize the upconverted electrical comb from 140 GHz to 220 GHz.

We demonstrate a new type of tunable comb generator by upconverting a train of pulses with an ultrawideband (UWB) mixer. The user can thereby: 1) move the electrical comb in the millimeter-wave frequency band, where a signal needs to be characterized, and 2) adjust the frequency spacing of the comb with the desired measurement frequency grid.

An illustration of this novel approach is proposed in Fig. 1. We first generate a stable train of pulses with broad energy content using a commercial comb generator [13]. The continuous wave (CW) signal driving the pulse generator determines the frequency spacing of the comb. The local-oscillator (LO) frequency defines the RF band of the electrical comb. To accomplish these functions, the monolithic microwave integrated circuit (MMIC) mixer requires UWB intermediate frequency (IF) and LO inputs. We describe the design methodology of the UWB mixer in Section II and present in Section III the measurement setup and the magnitude of the spectrum of the comb, measured from 140 GHz to 220 GHz. In Section IV, we discuss potential improvements and the use of this new approach to a millimeter-wave phase reference.

II. UWB Mixer Design

A variety of mixers using resistive [16], [17], transconductance [18], [19], Gilbert cell [20], [21], single-balanced [22], and micromixer [23] topologies have been reported above 100 GHz. To maximize the conversion gain and achieve high IF and LO rejection, we chose to design our mixer with a Gilbert cell. A simplified electrical schematic of the mixer is illustrated in Fig. 2(a).

We implemented a differential pair that acts as an active balun at the IF and LO input ports, instead of passive baluns

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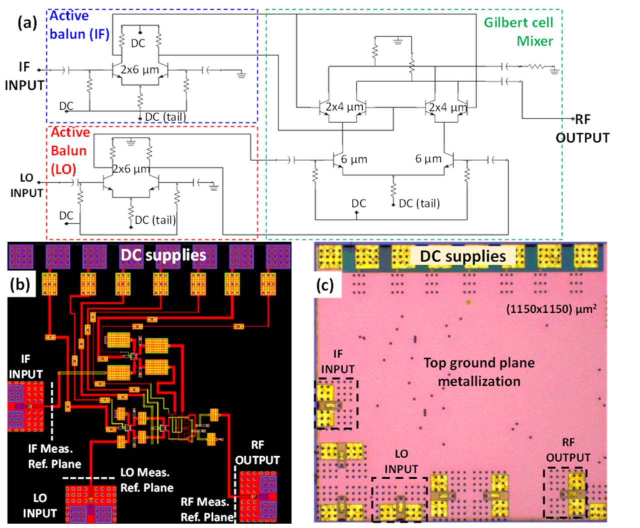

Fig. 2. UWB upconverter MMIC mixer. (a) Simplified electrical schematic. (b) Layout. (c) Photography.

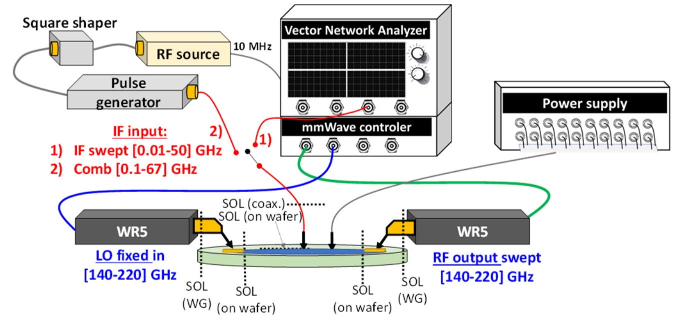

Fig. 3. Measurement setup of the upconverter mixer.

that would considerably limit the bandwidth. This arrangement allows us to feed the IF input with a broadband signal, from 50 MHz to the upper end of the millimeter waveband. The LO frequency can be chosen anywhere above 67 GHz. The two inputs (IF and LO) and the RF output of the mixer are intentionally not matched to keep a broadband operation. The reflection coefficients of the circuit approximately correspond to the reflection coefficients of the transistors used in the design. A resistor may be added at the IF input of the mixer to limit the multiple reflections between the two devices.

We designed the MMIC mixer in an indium phosphide (InP) 130 nm heterojunction bipolar transistor (HBT) process. A full description of the technology may be found in [24]. The passive elements were simulated using a planar electromagnetic (EM) simulator, and we used the foundry's nonlinear transistor's model to simulate the active mixer. The layout and a photography of the MMIC are shown in Fig. 2(b) and (c), respectively.

III. Characterization of the UWB Mixer

A. Measurement Setup

We used WR5 extenders and a nonlinear vector network analyzer to characterize the upconverter mixer from 140 GHz to 220 GHz. We switched from two different setups on the IF port, as illustrated in Fig. 3. First, we applied a CW signal from 10 MHz to 50 GHz to feed the IF input of mixer. We then connected the comb generator, driven by a square wave shaper and an external CW source, to the IF input of the mixer.

We performed one-port two-tier calibrations [short-open-load (SOL)] and absolute power calibration at each port of the mixer to measure the mixer's performance directly on-wafer. We measured the input and output power at each port of the circuit when performing single-tone characterization. However, we only measured the LO and RF characteristics when we applied a train of pulses at the IF input since we used an external comb generator. The main limitation of the measurement setup was in the power delivered on-wafer at the LO input port, −16 dBm. This limitation significantly reduced the RF output power and the conversion gain of the mixer. We used the microwave uncertainty framework [25] to calibrate the measurements.

B. CW Signal Applied at the IF Input

We first characterized the mixer with a CW signal at the IF input that we swept from 10 MHz to 50 GHz in 10 MHz steps. The IF input power was measured on-chip and corresponds to a ramp starting from −16 dBm at 10 MHz to −28 dBm at 50 GHz. We characterized the mixer for a 140 GHz and 180 GHz LO frequency. The measurement and simulation results are presented in Fig. 4.

We obtained a good agreement between the measured and simulated RF performance when the LO frequency was fixed at 140 GHz. The conversion gain varies from +3.2 dB (−13.8 dBm P_{OUT}) at 142.65 GHz to −14 dB (−42 dBm P_{OUT}) at 190 GHz. However, when we set the LO frequency to 180 GHz, we observed some discrepancies that are mainly caused by the spurious content in the waveguide extenders, inaccuracy in the conversation gain of the HBT model in the [140–220] GHz frequency band and unbalanced effects not captured in the circuit simulation. The measured conversion gain varies from +1.4 dB at 142.65 GHz to −19.8 dB at 204.23 GHz. Note that the high rejection of the RF tones around the LO frequencies (at 140 GHz and 180 GHz) is caused by the Gilbert cell itself that suppresses the IF and LO frequency contents.

C. Broadband Electrical Comb Applied at the IF Input

We connected the pulse generator to the IF input of the mixer. The pulse generator provides a stable 50 GHz electrical comb with a 500 MHz and 2 GHz spacing. We measured the upconverted RF characteristics when the LO frequency was set at 140 GHz and 180 GHz. The measurement and simulated results are presented in Fig. 5. We measured a comb from 140.5 GHz (and 142 GHz) to 190 GHz when the LO was fixed at 140 GHz. However, when the LO frequency was placed at 180 GHz, we obtained an electrical comb that entirely covered the WR5 band. With a 500 MHz spacing, the output power of the comb varies from −35.5 dBm at 180.5 GHz to −81.1 dBm at 214 GHz. The discontinuities in the magnitude of the spectrum are caused by the spurious content in the waveguide extenders that modifies the RF mixing products. However, the measured output power follows the trend predicted by our simulations. The pulse characteristics used in the simulator are based on the manufacturer's

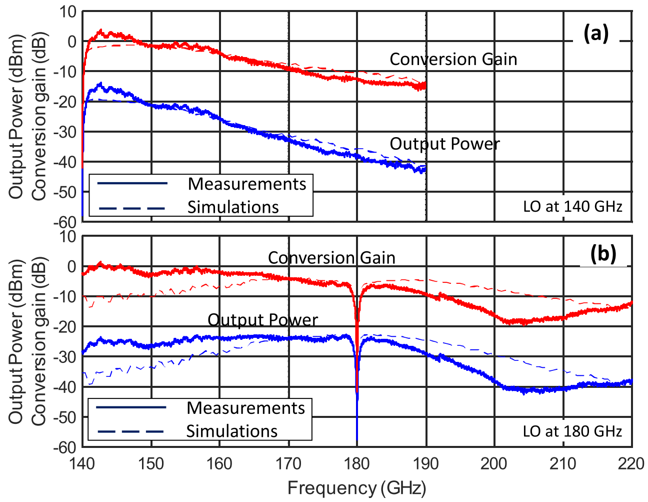

Fig. 4. RF performance of the mixer with CW IF 0.01–50 GHz. (a) LO frequency is set at 140 GHz. (b) LO frequency is set at 180 GHz. LO input power is set at −16 dBm.

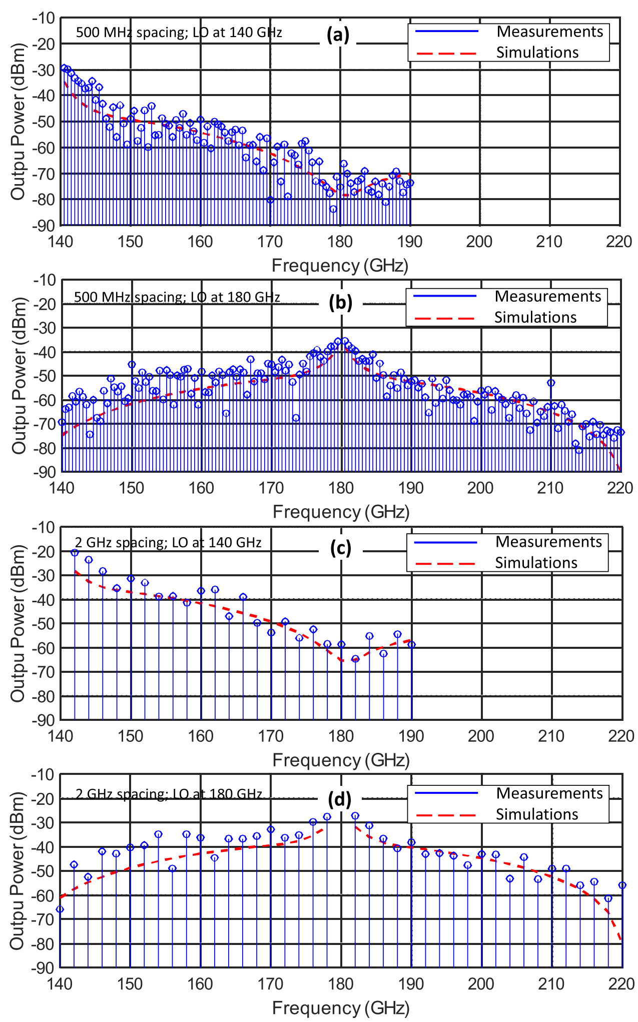

Fig. 5. Outpower power of the spectrum when the mixer is fed with a broadband comb at the IF input. (a) IF spacing: 500 MHz and LO: 140 GHz. (b) IF spacing: 500 MHz and LO: 180 GHz. (c) IF spacing: 2 GHz and LO: 140 GHz. (d) IF spacing: 2 GHz and LO: 180 GHz. LO input power is set at −16 dBm.

data [13]. We repeated the measurement and obtained the same comb characteristics.

TABLE I
COMPARISON OF BROADBAND ELECTRICAL COMB GENERATORS

References	f_{min} *(GHz)*	f_{max} *(GHz)*	*Δf (GHz)*	*Min. output power (dBm)*	*Type*
[4]	-	20	1.0	-13.8	NLTL
[27]	0.01	26.5	0.01	-99.0	HPR
[5]	0.6	30	0.6	-20	NLTL
[9]	0.5	50	0.5	> -57 *	SRD
[6]	1	50	1	> -30 *	NLTL
[11]	5	50	5	> -70 *	JJ
[28]	0.32	50	0.32	> -60 *	HPR
[10]	1.2	67	1.2	-	SRD
[13]	0.01	67	0.01	> -90 *	SSPG
[7]	5	70	5	-29.5	NLTL
[14]	1	110	1	-48.7	SSPG
This work	140	220	0.5	-81.1	SSPG + UWB Mixer

** Graphic estimation of the output power. NLTL: Non Linear Transmission Line. HPR: Harmonic Phase Reference. SRD: Step Recovery Diode. JJ: Josephson Junction. SSPG: Split Signal Pulse Generator. UWB: Ultrawideband.*

IV. CONCLUSION AND DISCUSSION

We presented a new approach to millimeter-wave comb generators by upconverting a broadband electrical comb with a UWB mixer. As shown in Table I, we demonstrated an electrical comb that operates from 140 GHz to 220 GHz, while other reported comb generators exhibit performance limited to 110 GHz or below. Although the measured bandwidth (80 GHz) is currently limited to the bandwidth of the WR5.1 waveguide extender, the actual bandwidth of the proposed comb generator is expected to be larger at a fixed LO frequency.

Substantial improvements can be directly implemented on-chip. A pulse generator, following the design approach presented in [14], can be integrated on-chip at the IF input of the UWB mixer. The capacitance value of dc blocks at the IF input of the mixer can be increased to reduce the “cut-on” frequency of the circuit down to 10 MHz. A multiplier and a differential amplifier could be added in the LO path of the mixer to provide the optimal LO power required on-chip.

An accurate measurement of the phase of the RF spectrum and a phase stability analysis of the full system will be required to use this new type of comb generator as a phase reference. As demonstrated in [14], the phase of the pulse is insensitive to large variations of the CW input signal that is used to drive the comb generator. A similar approach can be adopted at the LO input of the mixer to avoid any amplitude variation in the RF spectrum. Above 100 GHz, the characterization of the RF comb could be performed with an EOS method [26] to accurately measure the intertone phase of the spectrum and use it for traceable calibration at millimeter-wave and THz frequencies.

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REFERENCES

[1] T. W. Crowe, B. Foley, S. Durant, K. Hui, Y. Duan, and J. L. Hesler, "VNA frequency extenders to 1.1 THz," in *Proc. Int. Conf. Infr., Millim., THz Waves*, Oct. 2011, p. 1, doi: 10.1109/irmmw-thz.2011.6105028.

[2] T. S. Clement, P. D. Hale, D. F. Williams, C. M. Wang, A. Dienstfrey, and D. A. Keenan, "Calibration of sampling oscilloscopes with high-speed photodiodes," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 8, pp. 3173–3181, Aug. 2006, doi: 10.1109/TMTT.2006.879135.

[3] M. J. W. Rodwell, M. Kamegawa, R. Yu, M. Case, E. Carman, and K. S. Giboney, "GaAs nonlinear transmission lines for picosecond pulse generation and millimeter-wave sampling," *IEEE Trans. Microw. Theory Techn.*, vol. 39, no. 7, pp. 1194–1204, Jul. 1991.

[4] M. Kintis et al., "An MMIC pulse generator using dual nonlinear transmission lines," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 6, pp. 454–456, Jun. 2007, doi: 10.1109/LMWC.2007.897799.

[5] *NLTL Comb Generator Datasheet*, document MLPNC-7103, MACOM Website, 2023.

[6] Picosecond Pulse Labs, "A new breed of comb generators featuring low phase noise and low input power," *Microw. J.*, vol. 49, no. 5, p. 278, 2006.

[7] S. Zhang, G. Fan, Q. Li, and C. Xu, "Wideband MMIC nonlinear transmission-line comb generator," in *Proc. Photon. Electromagn. Res. Symp.-Fall (PIERS-Fall)*, Dec. 2019, pp. 794–799, doi: 10.1109/PIERS-Fall48861.2019.9021433.

[8] H. T. Friis, "Analysis of harmonic generator circuits for step recovery diodes," *Proc. IEEE*, vol. 55, no. 7, pp. 1192–1194, Jul. 1967.

[9] Q. Li, W. Jiang, Y. Xu, and F. Nian, "Analysis and design of wideband comb generator based on SRD," in *Proc. Int. Conf. Microw. Millim. Wave Technol. (ICMMT)*, vol. 1, May 2012, pp. 1–3, doi: 10.1109/ICMMT.2012.6229897.

[10] T. Harzheim, H. Heuermann, and M. Marso, "An adaptive biasing method for SRD comb generators," in *Proc. German Microw. Conf. (GeMiC)*, Mar. 2016, pp. 289–292, doi: 10.1109/GEMIC.2016.7461613.

[11] A. A. Babenko et al., "Characterization of a Josephson junction comb generator," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Aug. 2020, pp. 936–939, doi: 10.1109/IMS30576.2020.9223811.

[12] D. B. Gunyan and J. B. Scott, "Pulse generator," U.S. Patent 7 423 470 B2, Sep. 9, 2008.

[13] *Comb Generator Datasheet*, document U9391G, Keysight Website, 2017.

[14] J. Cheron et al., "A 110 GHz comb generator in a 250 nm InP HBT technology," *IEEE Microw. Wireless Compon. Lett.*, vol. 32, no. 6, pp. 736–739, Jun. 2022, doi: 10.1109/LMWC.2022.3164511.

[15] P. D. Hale, K. A. Remley, D. F. Williams, J. A. Jargon, and C. M. J. Wang, "A compact millimeter-wave comb generator for calibrating broadband vector receivers," in *Proc. 85th Microw. Meas. Conf. (ARFTG)*, May 2015, pp. 1–4, doi: 10.1109/ARFTG.2015.7162894.

[16] S. E. Gunnarsson, N. Wadefalk, I. Angelov, H. Zirath, I. Kallfass, and A. Leuther, "A 220 GHz (G-band) microstrip MMIC single-ended resistive mixer," *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 3, pp. 215–217, Mar. 2008, doi: 10.1109/LMWC.2008.916819.

[17] Y. Karandikar, H. Zirath, Y. Yan, and V. Vassilev, "Compact integration of sub-harmonic resistive mixer with differential double slot antenna in G-band using 50nm InP-HEMT MMIC process," in *Proc. IEEE Compound Semiconductor Integr. Circuit Symp. (CSICS)*, Oct. 2012, pp. 1–5, doi: 10.1109/CSICS.2012.6340081.

[18] Y. Li et al., "A high conversion gain 210-GHz InP DHBT sub-harmonic mixer using gain-enhanced structure," *IEEE Access*, vol. 7, pp. 101453–101458, 2019, doi: 10.1109/ACCESS.2019.2930800.

[19] Y. Yan, M. Bao, S. E. Gunnarsson, V. Vassilev, and H. Zirath, "A 110–170-GHz multi-mode transconductance mixer in 250-nm InP DHBT technology," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 9, pp. 2897–2904, Sep. 2015, doi: 10.1109/TMTT.2015.2459676.

[20] M. Seo et al., "A single-chip 630 GHz transmitter with 210 GHz sub-harmonic PLL local oscillator in 130 nm InP HBT," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2012, pp. 1–3, doi: 10.1109/MWSYM.2012.6259745.

[21] I. Lee, S. Kim, and S. Jeon, "H-band down-conversion and up-conversion mixers with wide IF bandwidth," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–4, doi: 10.1109/MWSYM.2016.7540050.

[22] A. Güner, T. Mausolf, J. Wessel, D. Kissinger, and K. Schmalz, "A 440–540-GHz subharmonic mixer in 130-nm SiGe BiCMOS," *IEEE Microw. Wireless Compon. Lett.*, vol. 30, no. 12, pp. 1161–1164, Dec. 2020, doi: 10.1109/LMWC.2020.3030315.

[23] D. Fritsche, P. Stärke, C. Carta, and F. Ellinger, "A low-power SiGe BiCMOS 190-GHz transceiver chipset with demonstrated data rates up to 50 Gbit/s using on-chip antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 9, pp. 3312–3323, Sep. 2017, doi: 10.1109/TMTT.2017.2677908.

[24] M. Urteaga, Z. Griffith, M. Seo, J. Hacker, and M. J. W. Rodwell, "InP HBT technologies for THz integrated circuits," *Proc. IEEE*, vol. 105, no. 6, pp. 1051–1067, Jun. 2017, doi: 10.1109/JPROC.2017.2692178.

[25] D. F. Williams, B. F. Jamroz, and A. Lewandowski, *NIST Microwave Uncertainty Framework*. Gaithersburg, MD, USA: National Institute of Standards and Technology, 2022. [Online]. Available: https://www.nist.gov/servicesresources/software/wafer-calibration-software

[26] P. D. Hale et al., "Traceability of high-speed electrical waveforms at NIST, NPL, and PTB," in *Proc. Conf. Precis. Electromagn. Meas.*, Jul. 2012, pp. 522–523, doi: 10.1109/CPEM.2012.6251033.

[27] *Harmonic Phase Reference Datasheet*, document HPR727A, AMCAD Engineering, 2021.

[28] D. Gunyan and Y.-P. Teoh, "Characterization of active harmonic phase standard with improved characteristics for nonlinear vector network analyzer calibration," in *Proc. 71st ARFTG Microw. Meas. Conf.*, Atlanta, GA, USA, Jun. 2008, pp. 1–7, doi: 10.1109/ARFTG.2008.4633334.