60 GHz Resonant Photoreceiver with an Integrated SiGe HBT Amplifier for Analog Radio-over-Fiber Links

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Abstract *A photoreceiver is presented for remote antennas in the unlicensed 60 GHz band utilizing an amplifier designed to present a matched impedance to a photodiode. The photoreceiver offers 29 dB higher gain than a reference photodiode over a 3 dB bandwidth of 5.7 GHz while consuming 33.6 mW. It is demonstrated up to 20 Gbps over 5 km SSMF at 4 Gbaud using QAM32 with an RMS EVM of 11.5%.*

Introduction

The V-band around 60 GHz has been allocated for unlicensed use across most of the world[1]. Industrial utilization of this band is increasing rapidly in communications and radar applications with multiple new products supporting it. It is considered a high priority millimeter-wave band by a majority of the industry[2]. Furthermore, telecommunications standardizing bodies such as the WiFi Alliance and 3GPP have incorporated this band into their standards[3]. The WiFi Alliance has already included it in IEEE 802.11ad and 801.11ay while the 3GPP has recently decided to extend 5G New Radio (5G-NR) frequency range 2 (FR2) to 71 GHz[4]. Besides, radar systems operating at 60 GHz have become mainstream with almost all major chipmakers offering solutions. Similar to the communications application domain, multiple-antenna and distributed systems are utilized in next generation demonstrators[5].

A big issue with moving to mmWave bands is the higher loss whether in free space or coaxial cables therefore multiple distributed antenna units are needed to provide coverage to an area. Signal generation hardware is typically consolidated to one place and shared as users move across the coverage area[6],[7]. Optical fiber is a low loss solution compared to copper and it is inexpensive to include in wiring harnesses or building cabling. Analog radio-over-fiber (ARoF) is considered to be the simplest and cheapest RoF topology and is therefore suitable for low-cost large scale deployments like cellular networks[8],[9].

A true low-cost solution has to be realized in high performance technologies that are cheap to mass produce and should be assembled in cost effective ways. SiGe BiCMOS is a good solution for mmWave amplifiers as it offers heterojunction bipolar transistors (HBTs) with f_T/f_{max} above 300 GHz and a favorable copper back-end-of-line (BEOL) metal stack with metal-insulator-metal (MIM) capacitors[10]. SiGe BiCMOS processes benefit from scaling efforts of CMOS technologies offering high yield, high integration and low cost manufacturing compared to III-V technologies.

This paper presents a low power narrowband photoreceiver operating at 60 GHz consisting of a SiGe BiCMOS amplifier and an InP UTC photodiode connected using wirebonds. The photoreceiver exhibits 29 dB higher gain than a reference photodiode over a 3 dB bandwidth of 5.7 GHz while consuming 33.6 mW. 17 dB of the gain improvement is due to amplifier gain and 14 dB due to resonant matching while there is 2 dB of combined loss in the input wirebonds and the output probe.

Narrowband Photoreceiver

The proposed narrowband photoreceiver (NBPhoRx) for low-cost remote antennas is shown in Fig. 1. It consists of a photodiode (PD) and a transimpedance low noise amplifier (TILNA). The TILNA was designed to present a conjugate matched load to the photodiode which is a low impedance source. The output of the TILNA is a standard 50Ω towards further RF chain components such as a power amplifier (PA) or antenna.

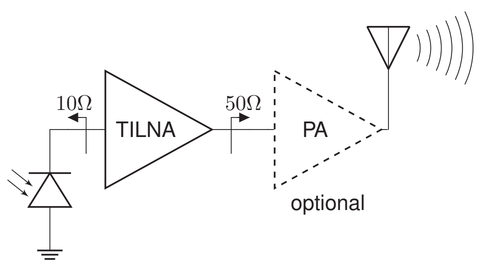

Fig. 1: A narrowband analog radio-over-fiber photoreceiver for low-cost remote antennas.

The TILNA is a three stage low noise amplifier with common emitter (CE) stages with inductive degeneration. The first stage has low input impedance and is optimized for low noise with sufficient gain while the second stage is optimized for medium noise and medium gain. The last stage is optimized for high gain and linearity. The photodiode is biased through an on-chip bias tee and the effects of wirebond interconnects are included in the design of the input network.

The TILNA was manufactured on a commercial 55nm SiGe BiCMOS process on a multi project wafer (MPW) run and was characterized with on-wafer measurements. It provides 17 dB of gain while consuming 33.6 mW and only occupies 0.25 mm^2 of silicon real estate including pads.

Frequency Response Characterization

The NBPhoRx was assembled with wirebonds on a PCB as shown in Fig. 2. Very short wirebonds were used for the RF interconnect between the PD and the TILNA while DC biasing was supplied through longer wirebonds. A lateral fiber was used for optical input while an RF probe was used for the output.

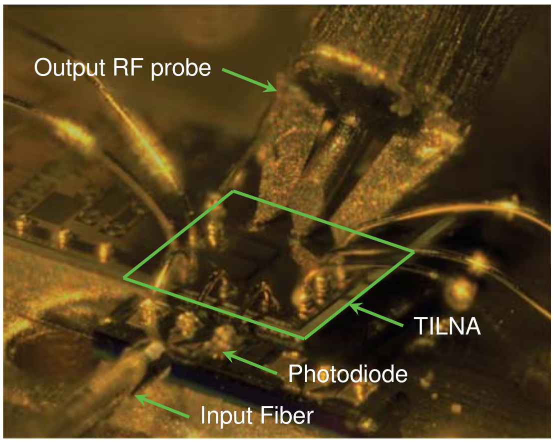

Fig. 2: Macrograph of NBPhoRx under test showing optical input fiber edge coupling and RF output probing

The performance of the NBPhoRx in an optical link was characterized up to 67 GHz using a vector network analyzer (VNA, Keysight PNA-X N5247B) and a testbench as shown in Fig. 3. The link was set up using a commercial laser (Tunics T100S-HP) and a Mach-Zehnder interferometer (MZI) modulator (Fujitsu FTM7937EZ) biased at quadrature at an optical wavelength of 1550 nm. The VNA was connected at ports 1 and 2 as indicated in the diagram. The VNA was calibrated to the end of its cables while a reference PD (Finisar XPDV2120-RA) was used to characterize the frequency response of the transmitter and to de-embed the characteristic of the NBPhoRx. The output probe was included in the measurements.

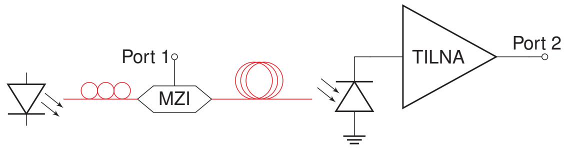

Fig. 3: Two port VNA testbench for NBPhoRx

The de-embedded frequency response of the NBPhoRx in an optical back-to-back (B2B) scenario can be seen in Fig. 4. The NBPhoRx is characterized to have a 29 dB gain at the center frequency with a 3 dB bandwidth of 5.7 GHz. Of the 29 dB gain, 17 dB is from active TILNA gain while 14 dB is from resonant matching. There is 2 dB of loss combined in the RF probe and input wirebonds.

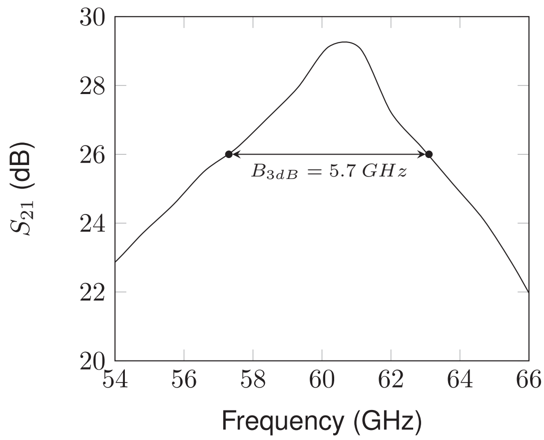

Fig. 4: Transmission response of NBPhoRx

Link Experiments

In order to demonstrate the transmission of real data using complex modulated waveforms, a testbench was set up as seen in Fig. 5. This is an extension of the previous testbench used for VNA measurements from Fig. 3. A transmitter was placed at port 1 and a receiver at port 2. The output probe and cable to the receiver were not calibrated out and form part of the link.

The transmitter comprises an arbitrary waveform generator (AWG, Keysight M8195A), an oscillator (Anritsu MG3696B), a mixer (VDI WR12eCCU) and three cascaded amplifiers (SHF M827B). The received signal from the NBPhoRx was demodulated with a real time oscilloscope (RTO, Keysight DSAZ634A).

The single carrier waveforms were generated with the AWG at an IF frequency of 11 GHz and upmixed to 60 GHz using a passive mixer and a

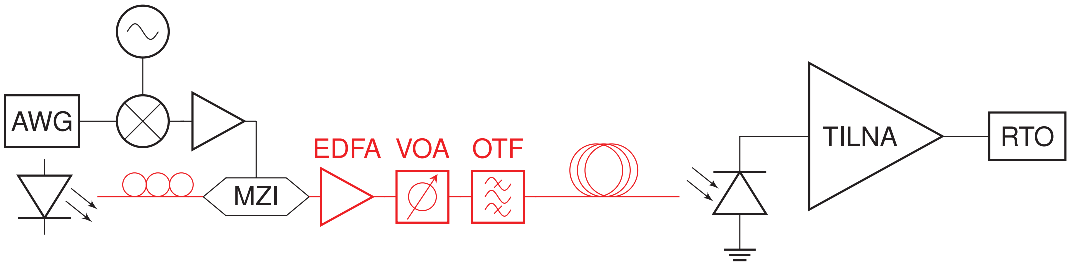

Fig. 5: Testbench for link experiments

LO of 35.5 GHz as the mixer module includes an LO frequency doubler. To overcome the insertion loss of the mixer, three amplifiers were used to amplify the low power (-30 dBm) signal to drive the MZI modulator with a signal power of 0 dBm which corresponds to 0.6 V V_{pp}. This is still very low and as the V_{pi} of the modulator in single drive is 3.6 V and because of this, the modulation depth of the test transmitter was very poor.

An Erbium-doped fiber amplifier (EDFA, Keopsys CEFA-C-HG) with an optical tunable filter (OTF, Santec OTF-350) was used to improve the optical signal of the test transmitter with a variable optical attenuator (VOA, Keysight N7762A) in the middle to control the power coming from the EDFA. The OTF was used to filter out some of the carrier power and one of the sidebands so the transmitted optical signal has a better modulation depth. This was transmitted over 5 km of standard single mode fiber (SSMF) to the NBPhoRx.

The output of the NBPhoRx was connected to a RTO using a 0.5 m RF cable which has 7 dB loss. The signals were demodulated in realtime and the obtained constellations are shown in Fig. 6. It can be seen the data rates of up to 20 Gbps are demonstrated at a symbol rate of 4 Gbaud using QAM32 at an EVM of 11.5%.

A comparison of the TILNA with the state-of-the-art can be seen in Table 1. It can be seen that this implementation is very compact and has low power consumption while offering good performance.

Conclusions

This work proposes and demonstrates an ARoF NBPhoRx for the unlicensed 60 GHz V-band based on a TILNA. The TILNA is designed to have

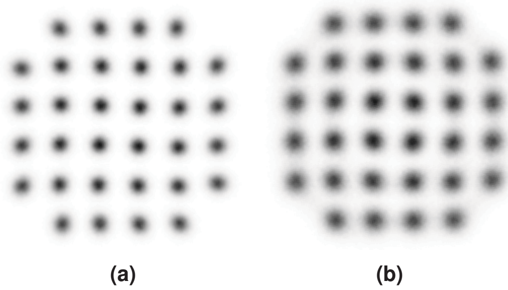

Fig. 6: Obtained constellations for QAM32 over 5 km SSMF (a) 1 Gbaud with EVM of 9% and (b) 4 Gbaud with EVM of 11.5%

a low input impedance to conjugate match the PD while the output impedance is 50Ω. The TILNA was manufactured on a commercial 55nm SiGe BiCMOS process and characterized to have 17 dB gain with 33.6 mW power consumption. The TILNA and PD were assembled on a PCB and electrically connected using wirebonds to form the NBPhoRX. The NBPhoRx has 29 dB higher gain than a reference photodiode of which 14 dB can be attributed to resonant matching. The NBPhoRx is demonstrated with complex modulated waveforms at data rates up to 20 Gbps over 5 km SSMF with a QAM32 modulated signal at 4 Gbaud with an EVM of 11.5%.

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Tab. 1: Comparison of the TILNA with the state-of-the-art

	Process Technology	Frequency	Active Gain	Size	Power Consumption
TILNA	55nm SiGe BiCMOS	60 GHz	17 dB	0.25 mm^2	33.6 mW
[11]	0.1μm GaAs pHEMT	28 GHz	24 dB	4.76 mm^2	160 mW
[12]	GaAs HEMT	60 GHz	24 dB	-	965 mW
[13]	0.1μm AlGaAs pHEMT	93 GHz	22 dB	11.2 mm^2	219 mW

References

[1] R. C. Daniels and R. W. Heath, “60 GHz wireless communications: Emerging requirements and design recommendations”, *IEEE Vehicular Technology Magazine*, vol. 2, no. 3, pp. 41–50, Sep. 2007.

[2] Intel Corporation, “Summary of Rel-17 email discussion on NR above 52.6GHz”, 3GPP, Document RP-191914, Sept. 2019.

[3] N. Patriciello, S. Lagen, B. Bojovic, and L. Giupponi, “NR-U and IEEE 802.11 Technologies Coexistence in Unlicensed mmWave Spectrum: Models and Evaluation”, *IEEE Access*, pp. 1–1, 2020.

[4] Qualcomm, “New WID on Extending current NR operation to 71 GHz”, 3GPP, Document RP-193229, Dec. 2019.

[5] A. Kanno, T. Umezawa, T. Kuri, N. Yamamoto, T. Kawanishi, and Y. N. Wijayanto, “Key technologies for millimeter-wave distributed RADAR system over a radio over fiber network”, in *2016 International Conference on Radar, Antenna, Microwave, Electronics, and Telecommunications (ICRAMET)*, 2016, pp. 1–6.

[6] C. Wu, H. Li, J. Van Kerrebrouck, A. Vandierendonck, I. L. de Paula, L. Breyne, O. Caytan, S. Lemey, H. Rogier, J. Bauwelinck, P. Demeester, and G. Torfs, “Distributed Antenna System Using Sigma-Delta Intermediate-Frequency-Over-Fiber for Frequency Bands Above 24 GHz”, *Journal of Lightwave Technology*, vol. 38, no. 10, pp. 2765–2773, 2020.

[7] G. Giannoulis, N. Argyris, N. Iliadis, G. Poulopoulos, K. Kanta, D. Apostolopoulos, and H. Avramopoulos, “Analog Radio-over-Fiber Solutions for 5G Communications in the Beyond-CPRI Era”, in *2018 20th International Conference on Transparent Optical Networks (ICTON)*, 2018, pp. 1–5.

[8] A. Matera, R. Kassab, O. Simeone, and U. Spagnolini, “Non-Orthogonal eMBB-URLLC Radio Access for Cloud Radio Access Networks with Analog Fronthauling”, *Entropy*, vol. 20, no. 9, 2018.

[9] Y. Tian, K. Lee, C. Lim, and A. Nirmalathas, “60 GHz Analog Radio-Over-Fiber Fronthaul Investigations”, *Journal of Lightwave Technology*, vol. 35, no. 19, pp. 4304–4310, 2017.

[10] P. Chevalier, W. Liebl, H. Rucker, A. Gauthier, D. Manger, B. Heinemann, G. Avenier, and J. Bock, “SiGe BiCMOS Current Status and Future Trends in Europe”, in *2018 IEEE BiCMOS and Compound Semiconductor Integrated Circuits and Technology Symposium (BCICTS)*, 2018, pp. 64–71.

[11] L. Bogaert, H. Li, K. Van Gasse, J. Van Kerrebrouck, J. Bauwelinck, G. Roelkens, and G. Torfs, “36 Gb/s Narrowband Photoreceiver for mmWave Analog Radio-over-Fiber”, *Journal of Lightwave Technology*, pp. 1–1, 2020.

[12] S. Fedderwitz, C. C. Leonhardt, J. Honecker, P. Muller, and A. G. Steffan, “A high linear and high power photoreceiver suitable for analog applications”, in *IEEE Photonics Conference 2012*, 2012, pp. 308–309.

[13] T. Umezawa, K. Kashima, A. Kanno, A. Matsumoto, K. Akahane, N. Yamamoto, and T. Kawanishi, “100-GHz Fiber-Fed Optical-to-Radio Converter for Radio- and Power-Over-Fiber Transmission”, *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 23, no. 3, pp. 23–30, 2017.