Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Phase Noise Aspects
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Abstract: This contribution considers important requirements of high signal quality for THz signal generation and demonstrates first results achieved for Stimulated Brillouin Scattering (SBS) method which enables line width of THz waves below 1 Hz with low phase noise.

Purpose: Input on THz signal quality discussion to THz Study Group “100G”.

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THz signal generation - Phase noise aspects

- Motivation
  - Proof and demonstrate technical feasibility with regard to phase noise requirements
  - Basic input to identify possible influence on standard specifications (PHY)
- Considerations on signal generation
  - Requirements
    - Line width, phase noise of signal carrier
  - Impairments
- Solution for phase noise optimization
  - Method and Experimental Setup
  - Test Results

Phase Noise Requirements

- Linewidth & phase noise requirements increase with an increasing number of phase states, since a certain level of phase noise is more critical for closer phase distances. In addition, the reduction of the symbol rate makes the phase noise more critical for modulation formats with a higher number of bits per symbol.

Modulation format	QPSK	8PSK	16PSK	Star 16 QAM	Square 16 QAM	Square 64 QAM
Linewidth / data rate	$2x10^{-4}$	$3x10^{-5}$	$6x10^{-6}$	$3x10^{-5}$	$3x10^{-6}$	$3x10^{-8}$
Linewidth @ 40Gbit/s	10 MHz	1.6 MHz	240 kHz	1.6 MHz	120 kHz	1.2 kHz

Table I: Linewidth requirements for a maximal receiver sensitivity penalty of 2dB @ BER=10^{-4} [1]

[1] Seimetz, M., "Laser Linewidth Limitations for Optical Systems with High-Order Modulation Employing Feed Forward Digital Carrier Phase Estimation," *Optical Fiber communication/National Fiber Optic Engineers Conference, 2008. OFC/NFOEC 2008. Conference on* , vol., no., pp.1,3, 24-28 Feb. 2008

Phase Noise Requirements

- Phase noise adds a random error to signal's phase, so that the constellation points spread in a radial pattern around the origin and errors occur when the points cross the decision regions.

	Single Sideband Phase Noise			
	1kHz	10kHz	100kHz	1MHz
OFDM [1]	-60 dBc/Hz	-75 dBc/Hz	-90 dBc/Hz	-110 dBc/Hz
DVB-T [2]	-80 dBc/Hz	-80 dBc/Hz	-132 dBc/Hz	-142 dBc/Hz
FDMA [3]	-60 dBc/Hz	-75 dBc/Hz	-90 dBc/Hz	-105 dBc/Hz
LTE [4]	-80 dBc/Hz	-94 dBc/Hz	-106 dBc/Hz	-145 dBc/Hz
EHF Satelite Communic. [5]	-80 dBc/Hz	-95 dBc/Hz	-95 dBc/Hz	-95 dBc/Hz

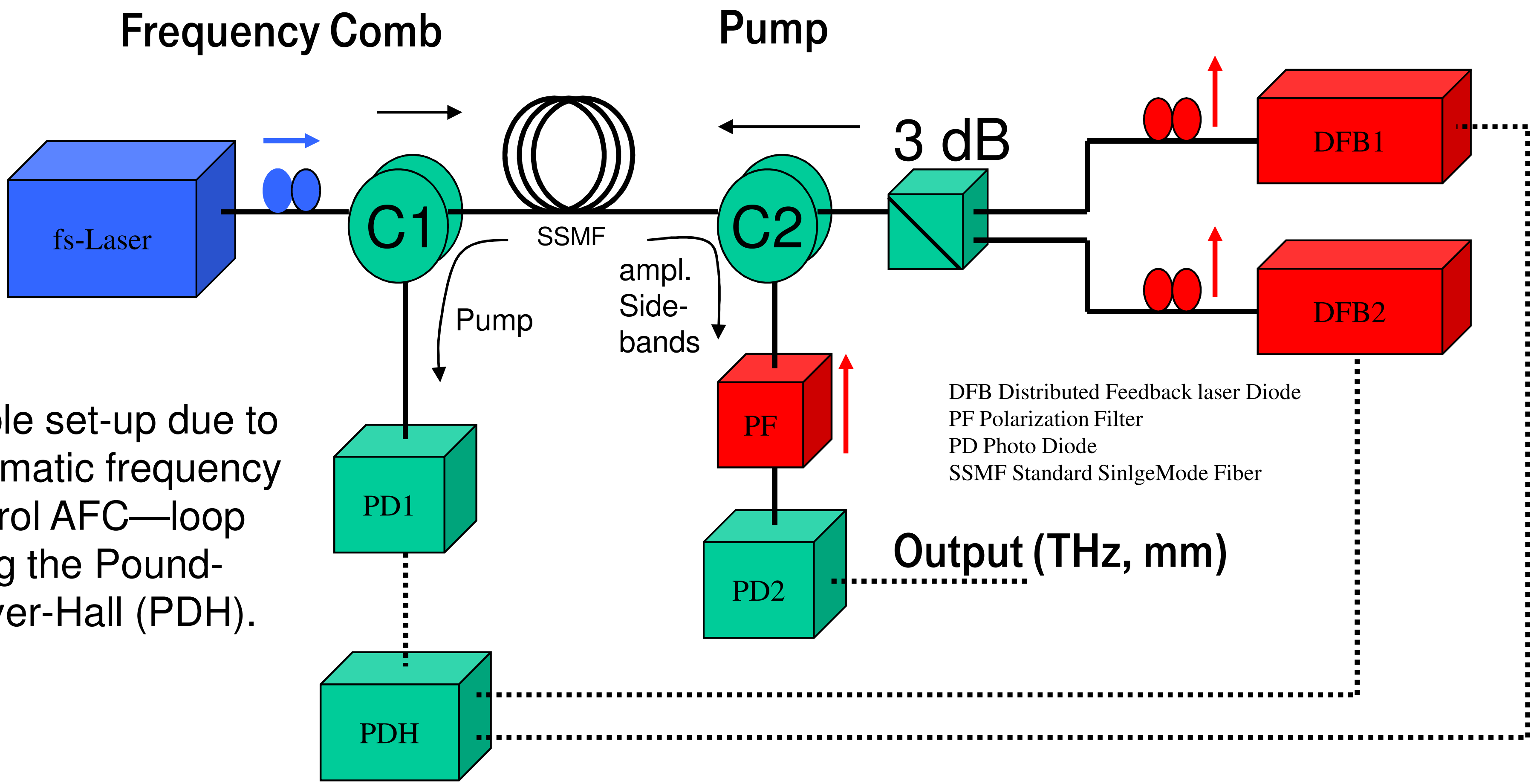
[1] Armada, A.G., "Understanding the effects of phase noise in orthogonal frequency division multiplexing (OFDM)," *Broadcasting, IEEE Transactions on* , vol.47, no.2, pp.153,159, Jun 2001
[2] Antoine, P.; Bauser, P.; Beaulaton, H.; Buchholz, M.; Carey, D.; Cassagnes, T.; Chan, T. K.; Colomines, S.; Hurley, F.; Jobling, D.T.; Kearney, N.; Murphy, A.C.; Rock, J.; Salle, D.; Cao-Thong Tu, "A direct-conversion receiver for DVB-H," *Solid-State Circuits, IEEE Journal of* , vol.40, no.12, pp.2536,2546, Dec. 2005.
[3] Rosati, S.; Corazza, G.E.; Vanelli-Coralli, A., "Coded SC-FDMA for broadband satellite return links," *Advanced Satellite Multimedia Systems Conference (ASMS) and 12th Signal Processing for Space Communications Workshop (SPSC), 2012 6th* , vol., no., pp.226,232, 5-7 Sept. 2012
[4] Kowlgi, S.; Mattheijssen, P.; Berland, C.; Ridgers, T., "EVM considerations for convergent multi-standard cellular base-station transmitters," *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on* , vol., no., pp.1865,1869, 11-14 Sept. 2011
[5] Cianca, E.; Rossi, T.; Yahalom, A.; Pinhasi, Y.; Farserotu, J.; Sacchi, C., "EHF for Satellite Communications: The New Broadband Frontier," *Proceedings of the IEEE* , vol.99, no.11, pp.1858,1881, Nov. 2011

THz signal generation: Optical heterodyning

- Generation:
  - 2 laser diodes
  - Fabry-Perot Electro-Optic modulator
  - MZM Sideband Generation
  - **Tunable Mode Locked Laser**
  - **femto-second (fs) laser**
- Separation:
  - WDM-Filter
  - Bragg Gratings
  - Wave Shaper (Finisar)
  - **Stimulated Brillouin Scattering**

➢ Method is based on fs laser and Stimulated Brillouin Scattering (SBS)

Experimental Setup

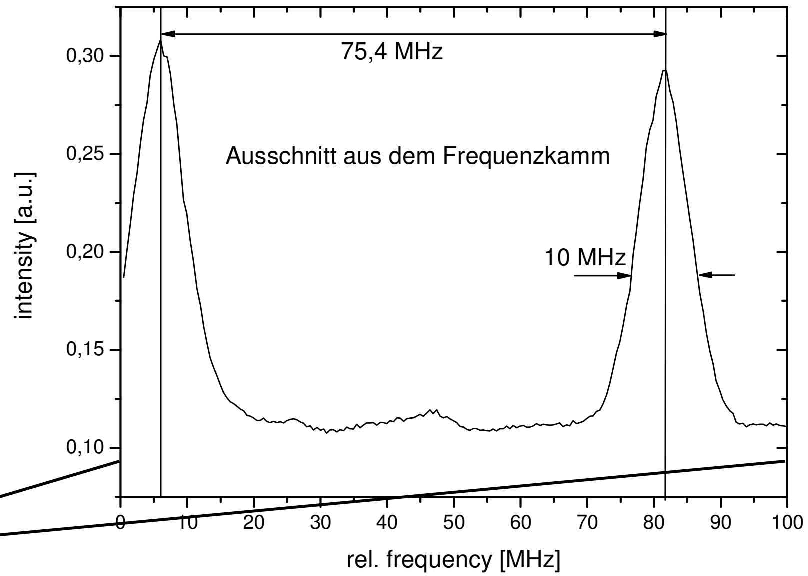


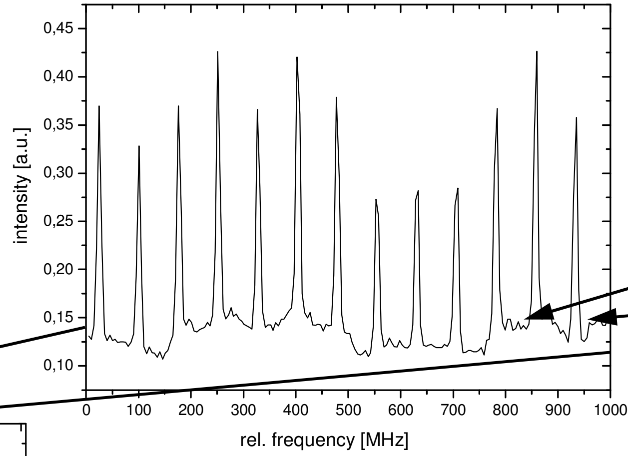
Stable set-up due to automatic frequency control AFC—loop using the Pound-Drever-Hall (PDH).

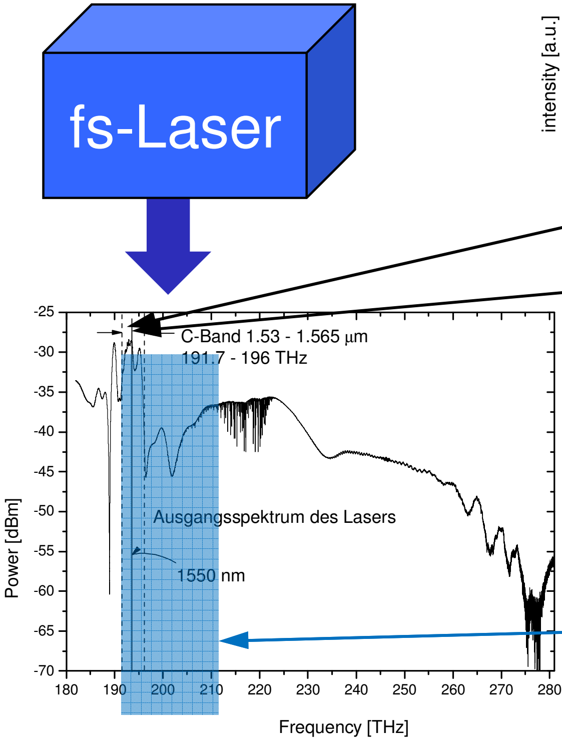
Optical small bandwidth amplification of two selected optical comb lines using the polarization assisted Stimulated Brillouin Scattering (SBS) gain of counter-propagating optical waves.

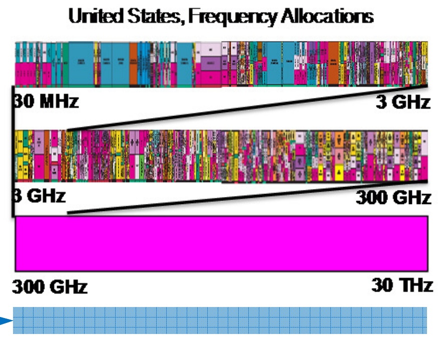
Generation of correlated optical comb lines using a mode-locked femto-second (fs) laser

- Comb-spectrum with >300.000 lines

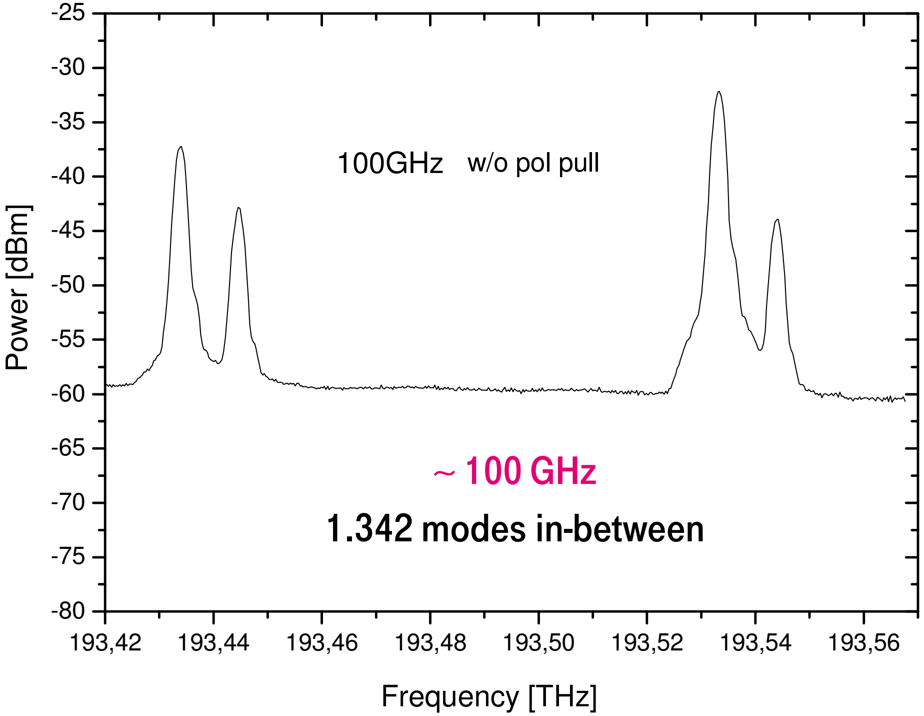


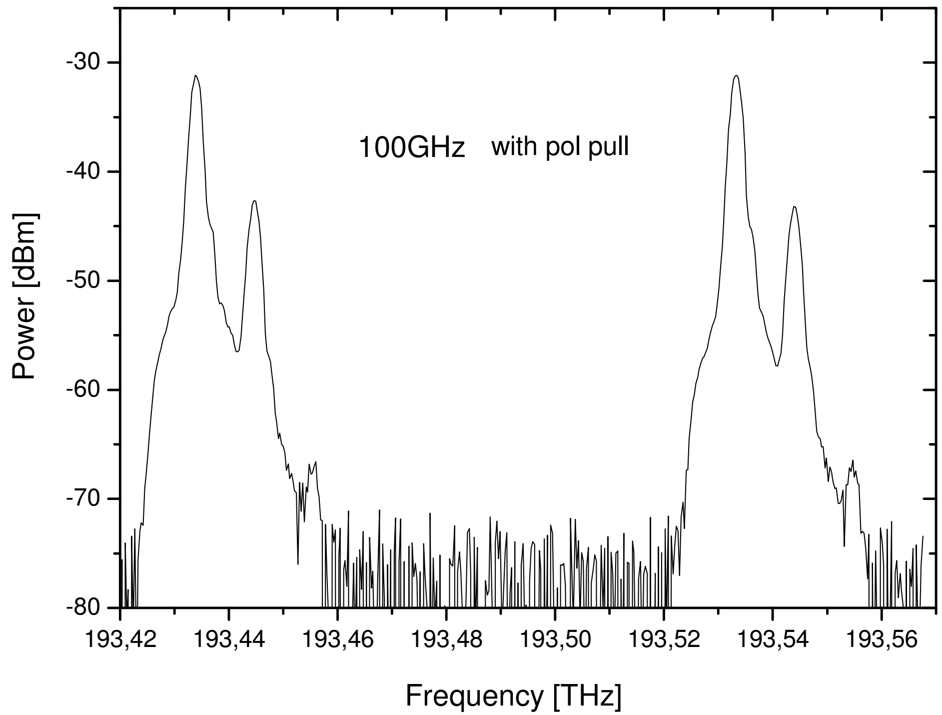






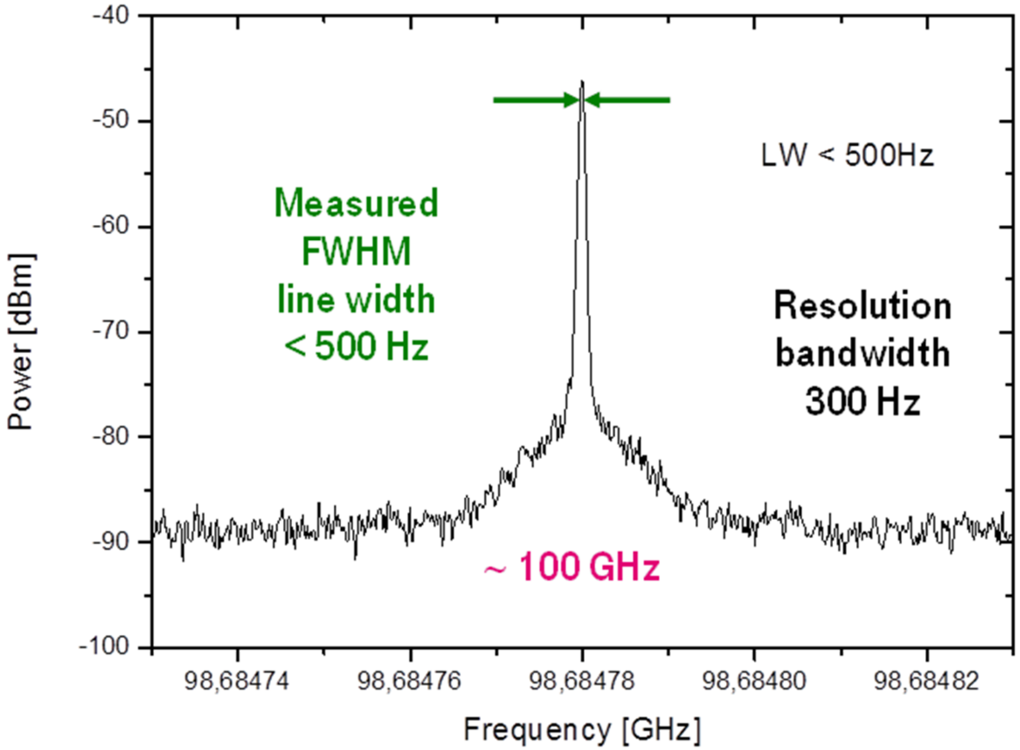
SBS amplification of 2 optical modes for 100 GHz generation

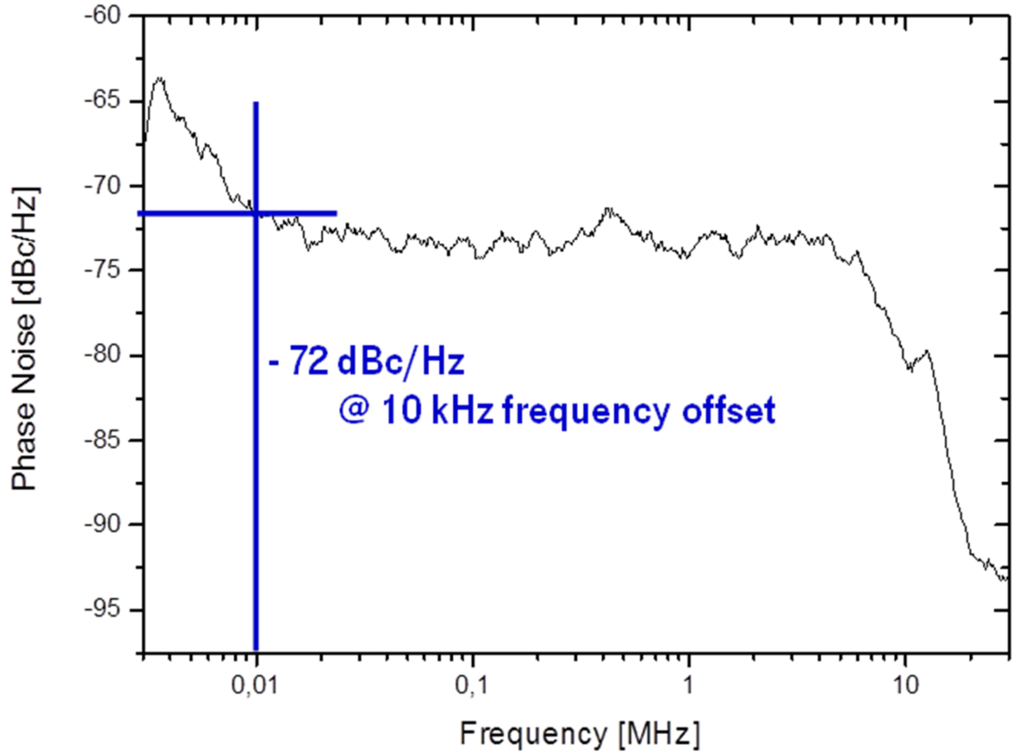




Amplification of two modes out of the spectrum of the fs-laser. There are 1342 modes between the two amplified ones. The remaining modes are suppressed due to the polarization pulling characteristics of SBS.

Phase noise measurements at 100 GHz

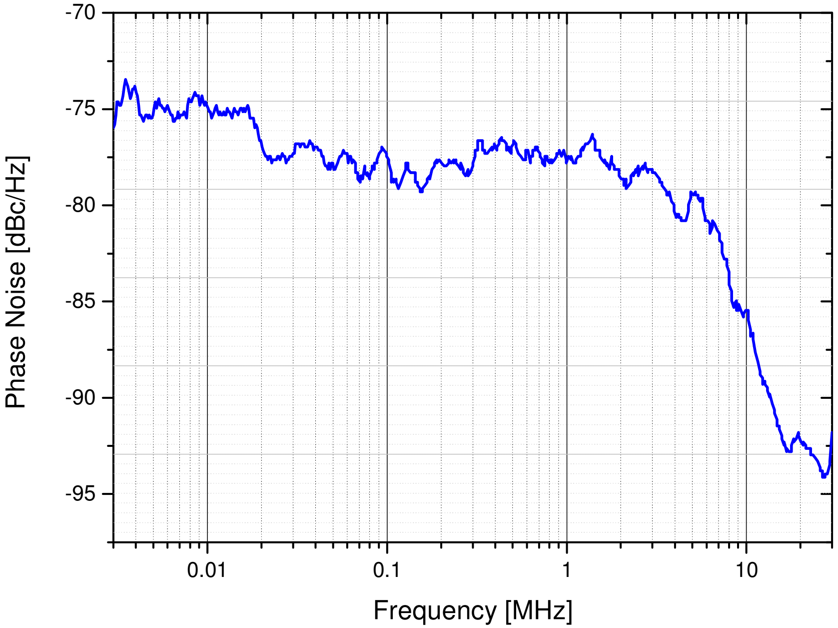




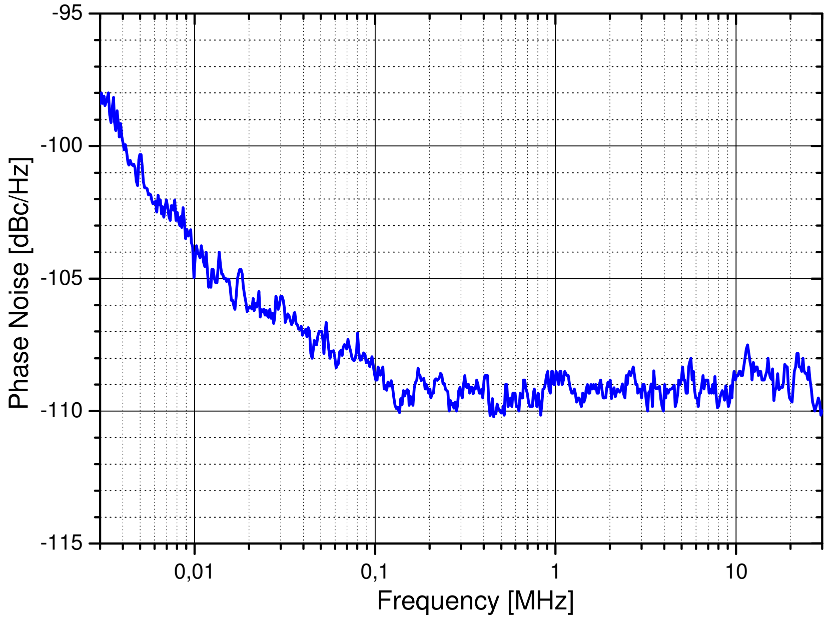
Generated mm-wave measured with an external electrical mixer at the ESA. Therefore the resolution bandwidth is restricted to 300Hz. The right figure shows the according phase noise measurement.

Phase Noise Measurement at 100Ghz

unoptimized

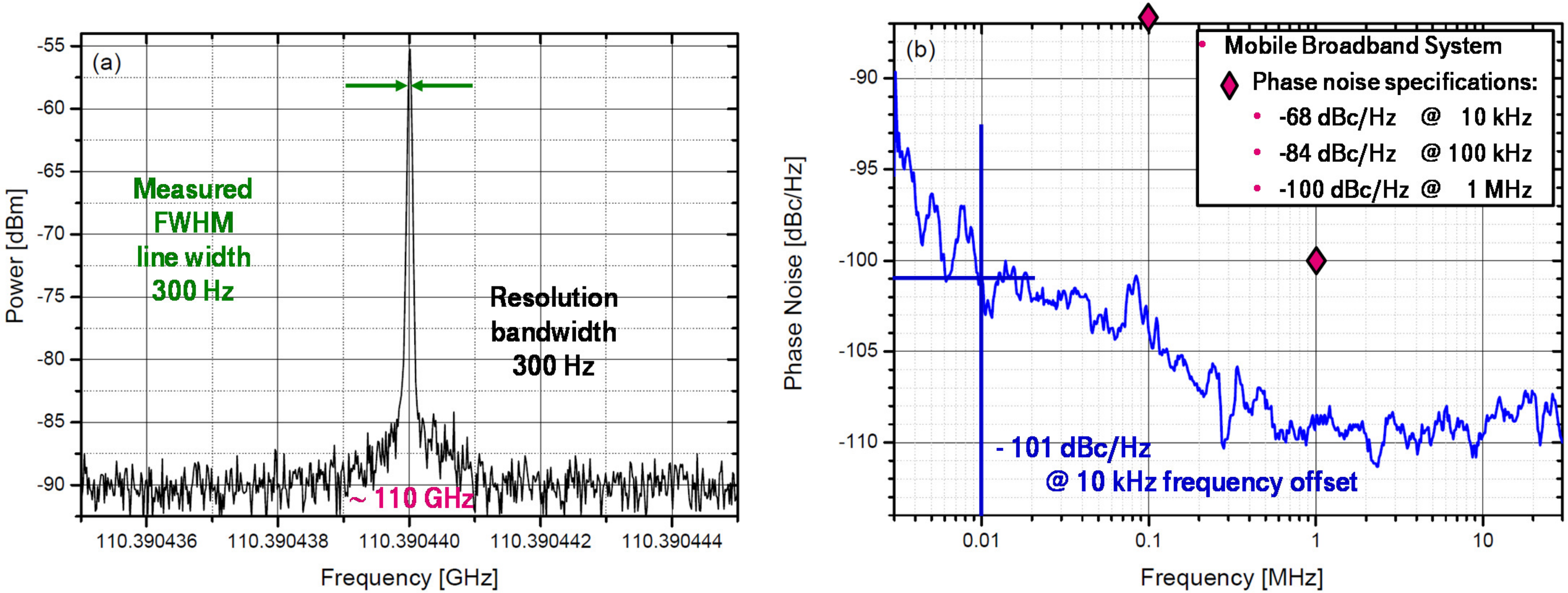


optimzed



- Optimization of fiber length, pump power and locking of laser diodes in order to reduce the generated noise. Left: 50km of fiber, high pump power; Right: 5km fiber and moderate pump power

Test results



Generated millimeter-wave signal with a frequency of 110.39044 GHz. The measured line-width was restricted by the resolution bandwidth of the ESA due to the used microwave mixers (<300 Hz). In (b) the phase noise measurement is shown.

M. Chelouche and A. Plattner, "Mobile broadband system (MBS): Trends and impact on 60 GHz band MMIC development," Electronics & Communication Engineering Journal, Volume 5, Issue 3, June 1993, p. 187 – 197

Comparison of different methods

Method	Frequency	Line-width	Phase-noise	Description of Method
(1)	75,4 MHz – 5 THz	< 1 Hz	-104 dBc/Hz @ 10 kHz	Stimulated Brillouin Scattering (SBS)
(2)	10 - 110 GHz	no meas., kHz range	-79 dBc/Hz @ 10kHz	Comb generated from phase modulator in a fiber loop with pump, optical injection locking
(3)	90 - 125 GHz	< 4 Hz	-75 dBc/Hz @ 100Hz	Single mode laser, MZM, planar light circuit with arrayed waveguide grating (spacing 60 GHz)
(4)	90 - 303 GHz	<2 Hz	-50 to -70 dBc/Hz @ 10kHz	Two external cavity diode lasers, phase lock to Ti:S laser frequency comb; free-space
(5)	0.1 - 1 THz	1 MHz	n/a	Two tunable single-freq. CW laser phase-locked independently to two frequency combs, combs all phase-locked to microwave freq. reference synthesized from a hydrogen maser linked to coordinated universal time
(6)	10 GHz – 3 THz	< 50 kHz	n/a	Two cw lasers phase locked to frequency comb, spectroscopy

(1) S. Preußler, N. Wenzel, R.-P. Braun, N. Owschimikow, C. Vogel, A. Deninger, A. Zadok, U. Woggon, T. Schneider, „Generation of ultra-narrow, stable and tunable millimeter- and terahertz- waves with very low phase noise“, Opt. Express 21, 23950-23962 (2013).
(2) S. Fukushima et.al., “Optoelectronic millimeter-wave synthesis using an optical frequency comb generator, optically injection locked lasers, and a unitraveling-carrier photodiode,” IEEE J. Lightwave Technol. 21, 3043–3051 (2003).
(3) A. Hirata et.al., “Low-phase noise photonic millimeter-wave generator using an AWG integrated with a 3-dB combiner,“ IEICE Trans. Electron. E88-C, 1458–1464 (2005).
(4) Q. Quraishi, et.al., “Generation of phase-locked and tunable continuous-wave radiation in the terahertz regime,” Opt. Lett. 30, 3231–3233 (2005).
(5) T. Yasui, et.al., “Continuously tunable, phase-locked, continuous-wave terahertz generator based on photomixing of two continuous-wave lasers locked to two independent optical combs,” J. Appl. Phys. 107, 033111 (2010).
(6) F. Hindle, et.al., ”Widely tunable THz synthesizer”, Applied Physics B 104, 763-768 (2011).

Conclusion

- Concept and experimental setup for generation of THZ carriers with low phase noise presented.
- Results of experimental tests
  - Generation of THz-waves with low phase noise
  - Line width below 1 Hz
  - -104 dBc/HZ @ 10 kHz
  - Applicable for all applications
- Contributes to PAR/5C of task group proposal by demonstrating technical feasibility with regard to higher phase noise requirements.
- Basic input to identify possible influence of achievable signal quality on development of standard specifications (PHY).
- It is proposed to include phase noise properties as a task group objective.