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Photonic Devices and Architectures for Generation, Processing and Detection of Mm-wave and THz signals

Prof. Pablo Acedo
Universidad Carlos III de Madrid

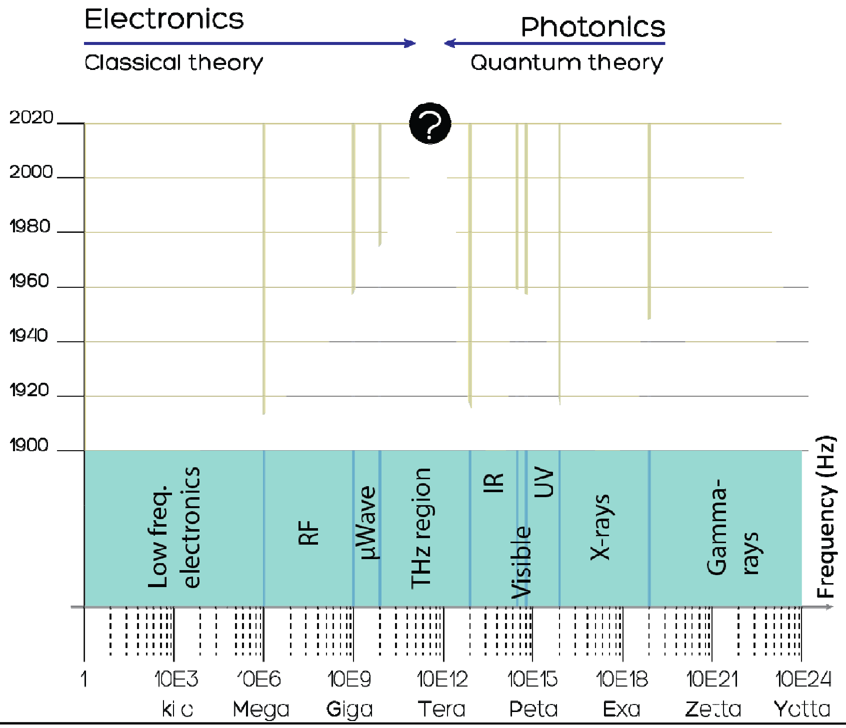
Outline

- Motivation: New Photonic Devices and Architectures for mm-wave and sub-THz generation, detection and processing .
- Photonic Techniques for mm-Wave and THz Signal Synthesis (Generation).
  - Fundamentals of Optical Heterodyning for Photonic signal Synthesis.
  - Revision of different techniques for photonic signal synthesis.
    - Single Source.
    - Dual(Multi)-Source.
  - Optical Frequency Combs Generators for Photonic Synthesis.
- Photonics Techniques for mm-wave and THz signal processing.
- Photonic Techniques for mm-wave and THz Signal Detection.
- Conclusions.

Motivation

Development of the EM Spectrum

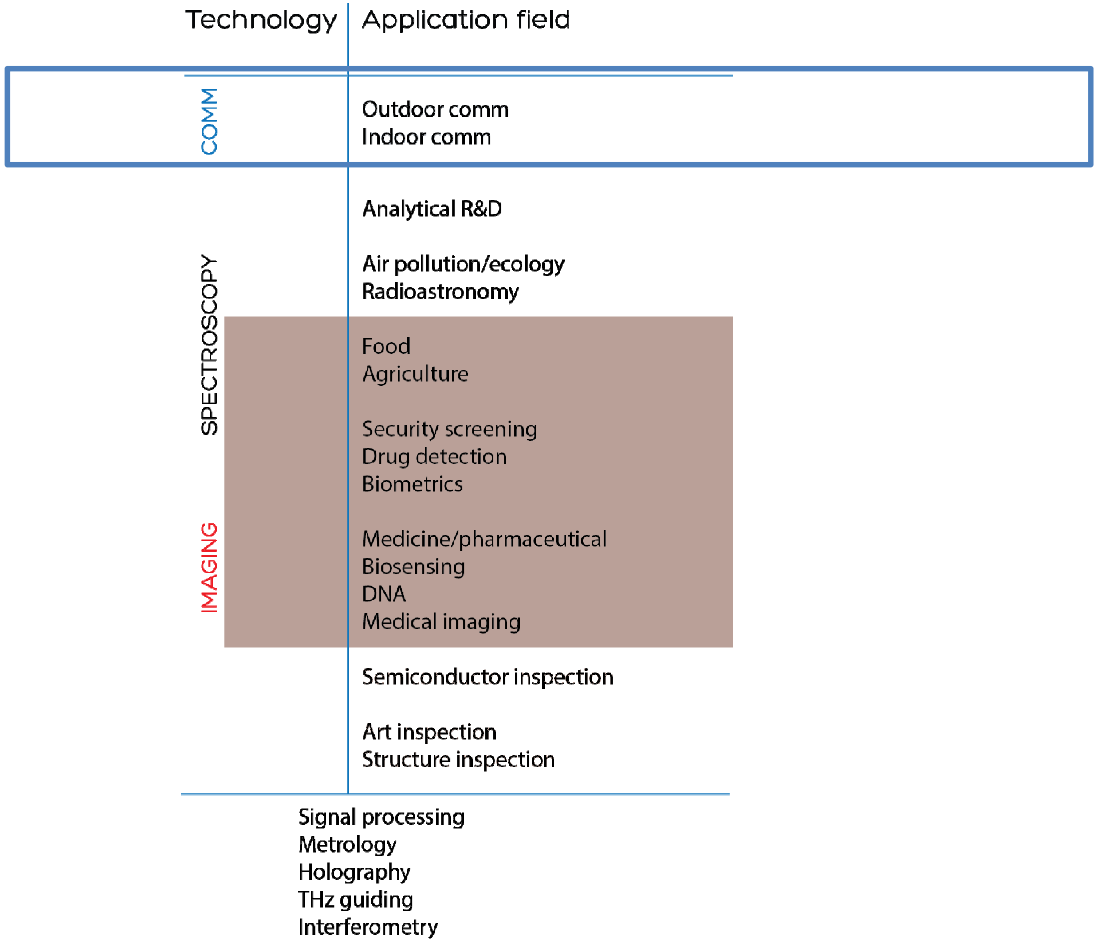
- Huge development of electronics and photonics in the last century…but not the “gap” between them: the THz region
- Technological limitations to build the technology (oscillators and detectors), especially coherent



Complete Access to the mm-Wave and THz Range. Interest

- Contactless identification of hidden objects and materials (security)
- Molecular resonances (spectroscopy)
- Non-ionizing radiation (medical/security applications)
- Atmospheric absorption (short range communications)

Applications: Communications.



Outdoor comm
Indoor comm

Analytical R&D

Air pollution/ecology
Radioastronomy

Food
Agriculture

Security screening
Drug detection
Biometrics

Medicine/pharmaceutical
Biosensing
DNA
Medical imaging

Semiconductor inspection

Art inspection
Structure inspection

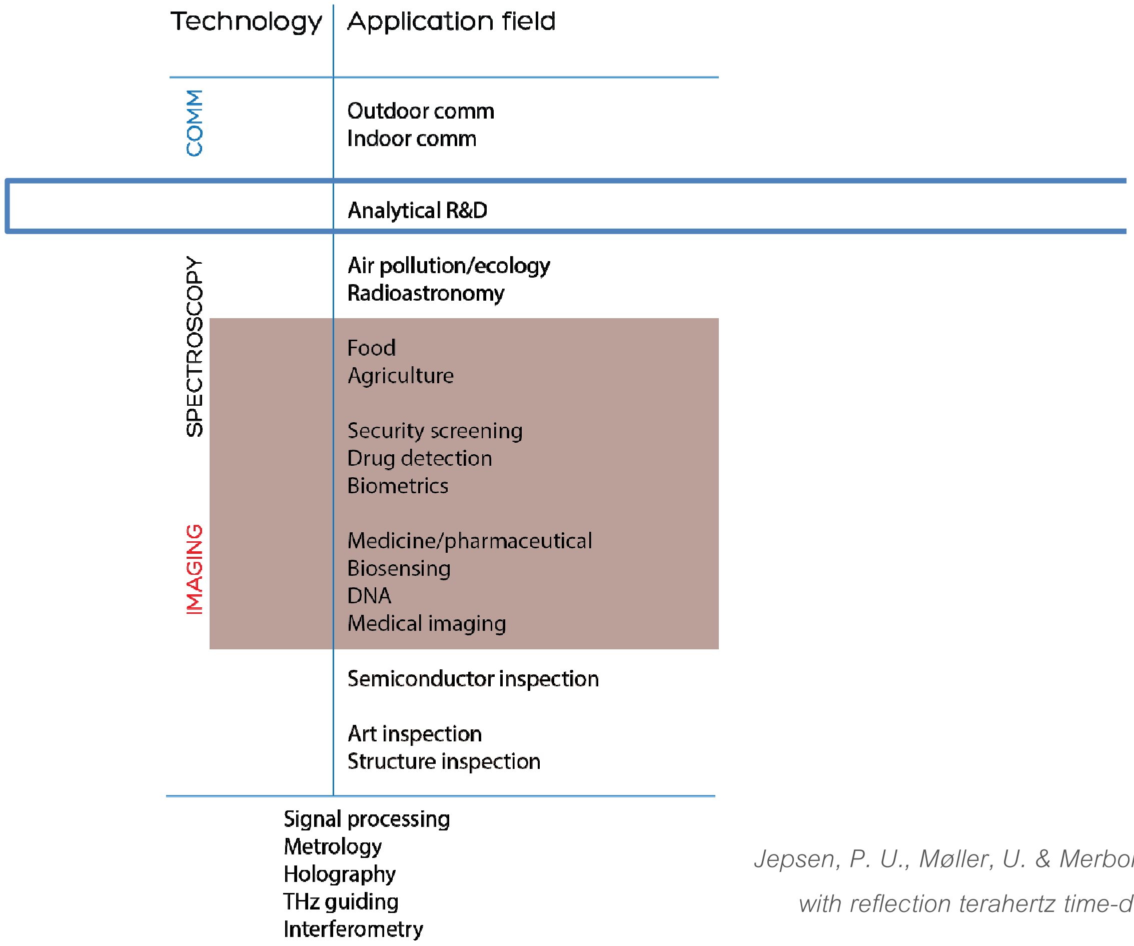
Signal processing
Metrology
Holography
THz guiding
Interferometry

Short range

High bandwidth

Toptica Photonics, toptica.com

Applications: Spectroscopy.



Technology | Application field

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SPECTROSCOPY

IMAGING

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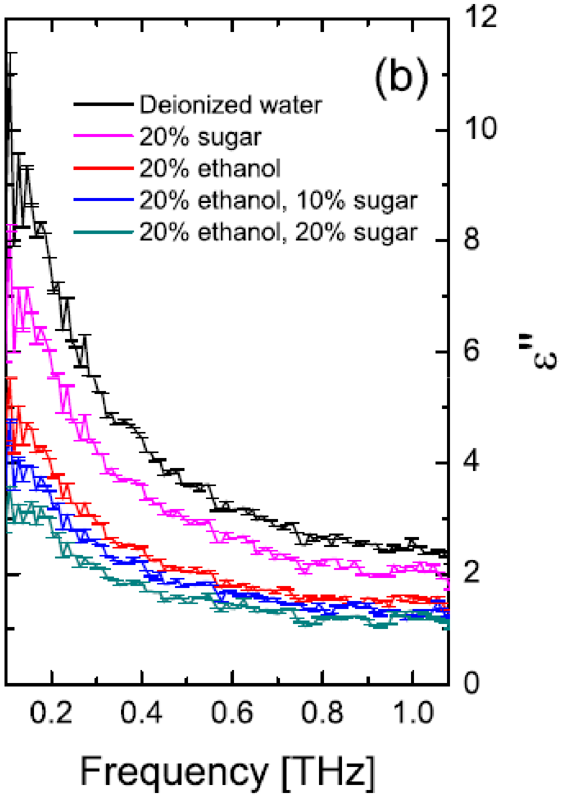
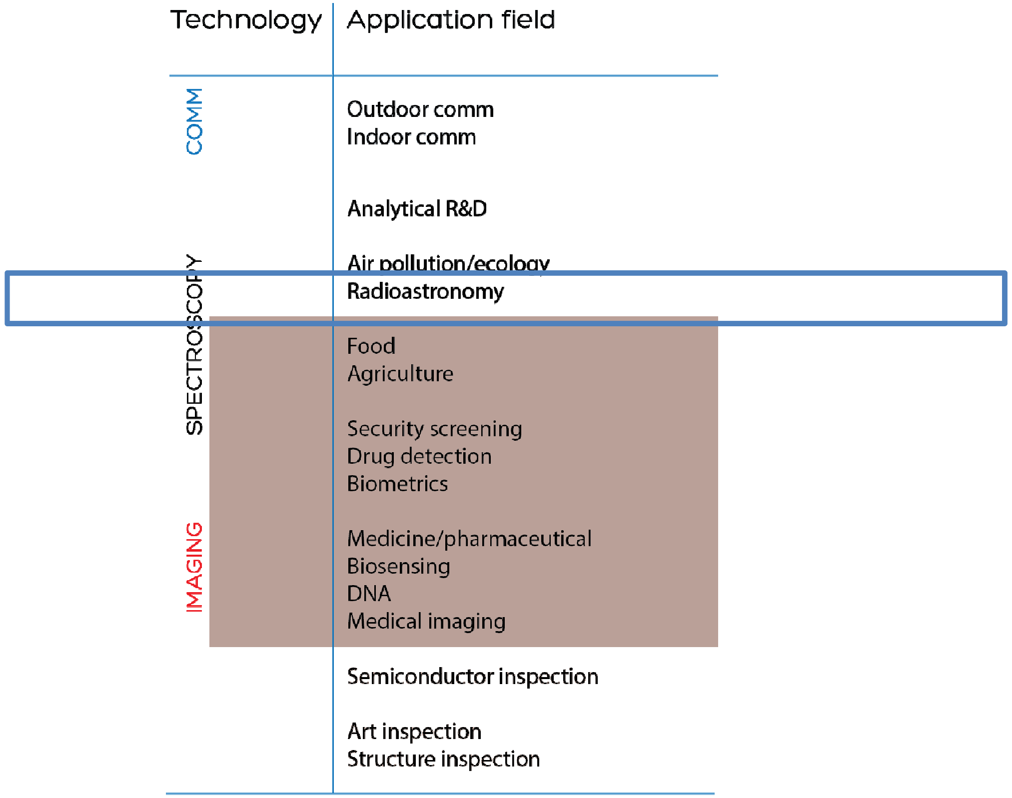


Jepsen, P. U., Møller, U. & Merbold, H. Investigation of aqueous alcohol and sugar solutions with reflection terahertz time-domain spectroscopy. Optics Express 15,(22) 14717 (2007)

Applications: Radioastronomy.



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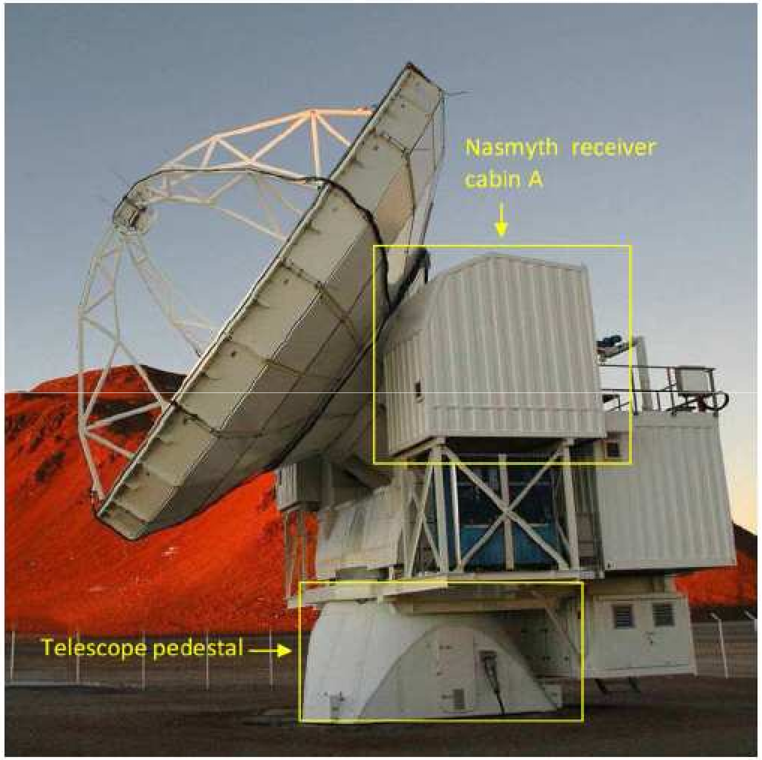
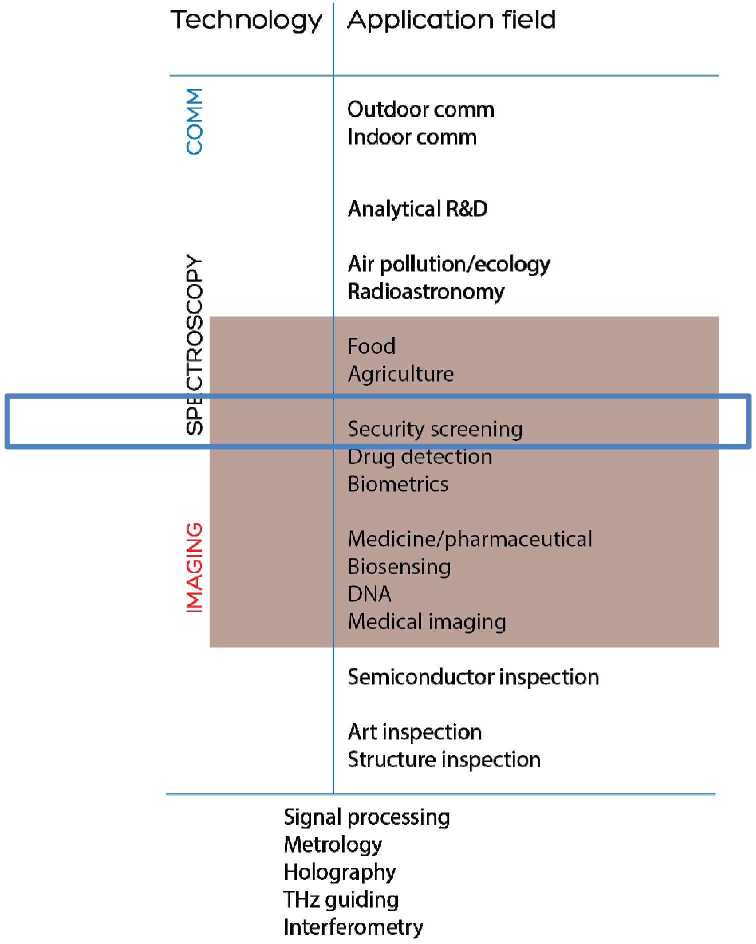


Cámara mayorga, I, Schmitz, A., Klein, tT, Leinz, C. & Gusten, R. First In-Field Application of a Full Photonic Local Oscillator to Terahertz Astronomy. IEEE Transactions on Terahertz Science and Technology 2,(4) 393–399 (2012).)

Applications: Imaging.



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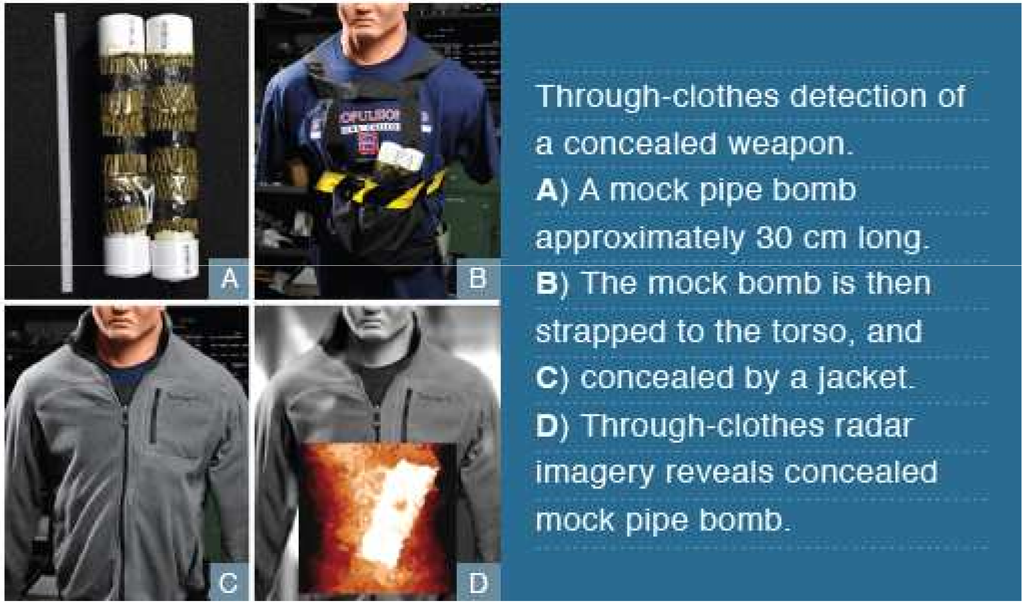
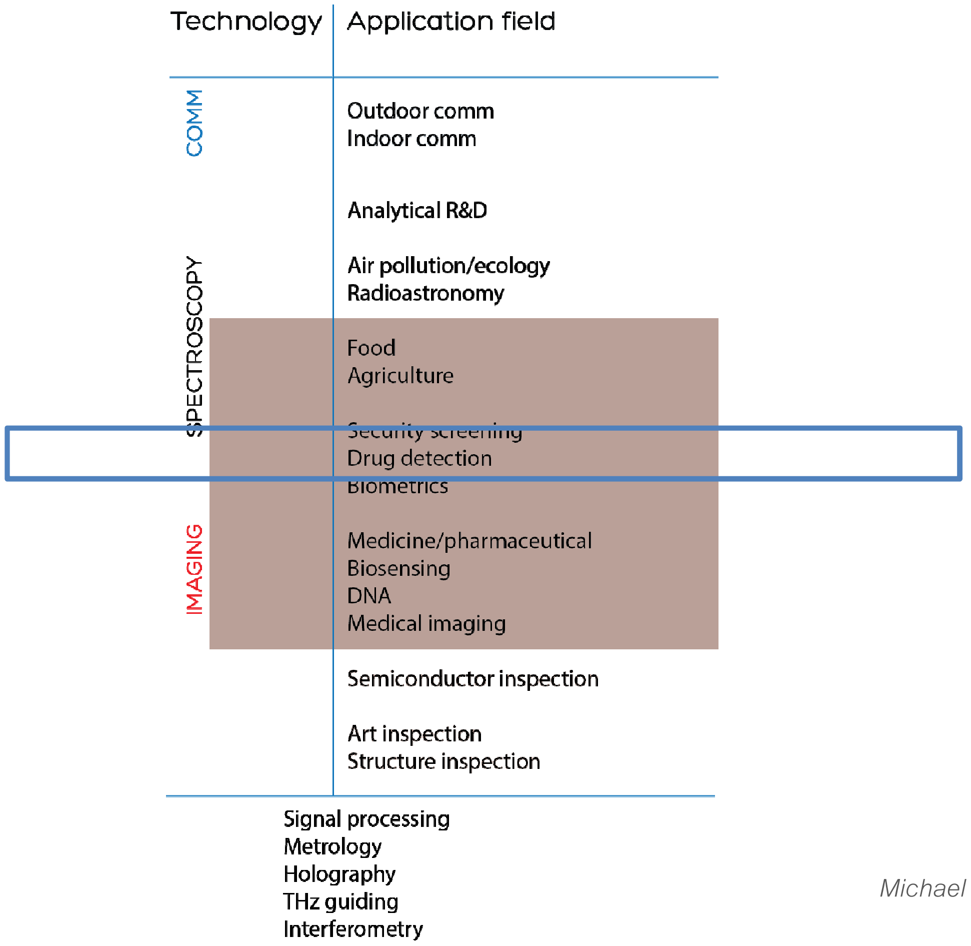


Through-clothes detection of a concealed weapon. **A)** A mock pipe bomb approximately 30 cm long. **B)** The mock bomb is then strapped to the torso, and **C)** concealed by a jacket. **D)** Through-clothes radar imagery reveals concealed mock pipe bomb.

Jet Propulsion Laboratory. California Institute of Technology, jpl.nasa.gov

Applications: Law Enforcement.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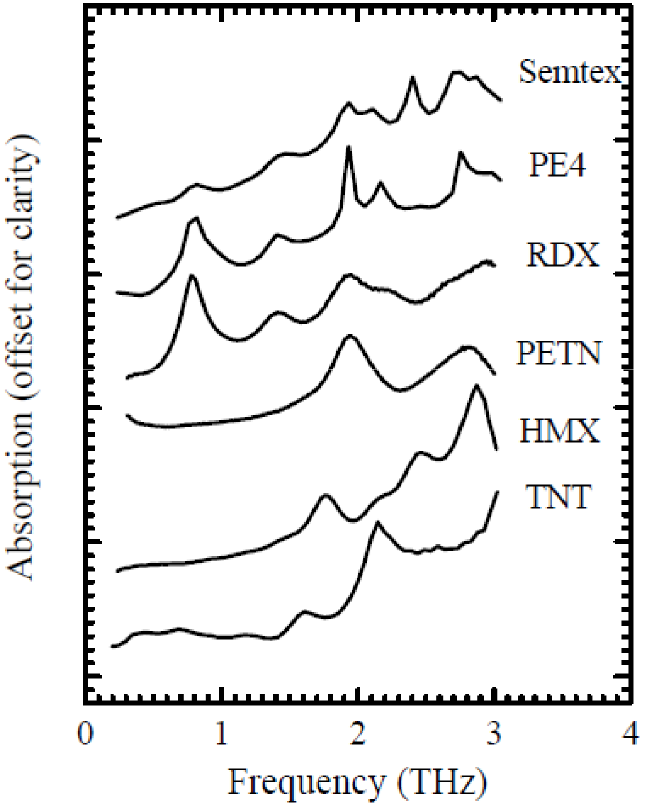
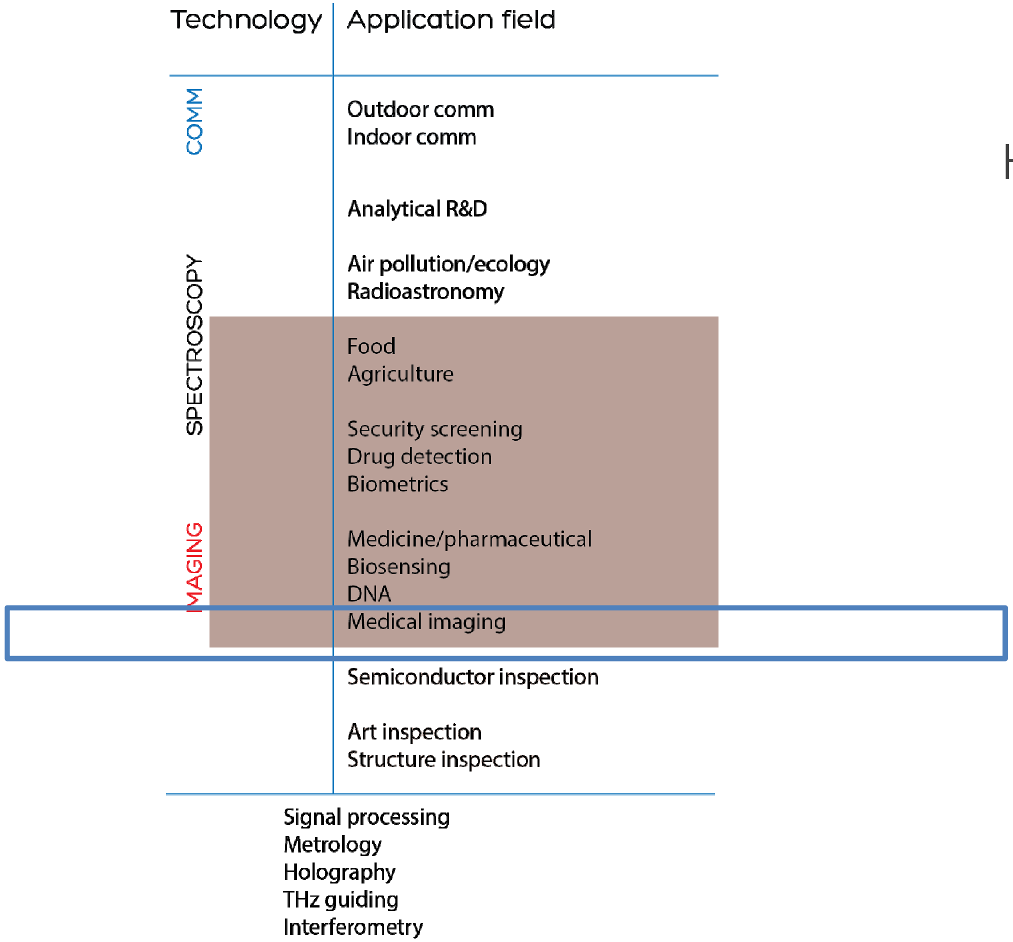


Michael C Kemp, Millimetre Wave and Terahertz Technology for the Detection of Concealed Threats – A Review. Proc. of SPIE Vol. 6402, 64020D, (2006)

Applications: Medical Imaging.



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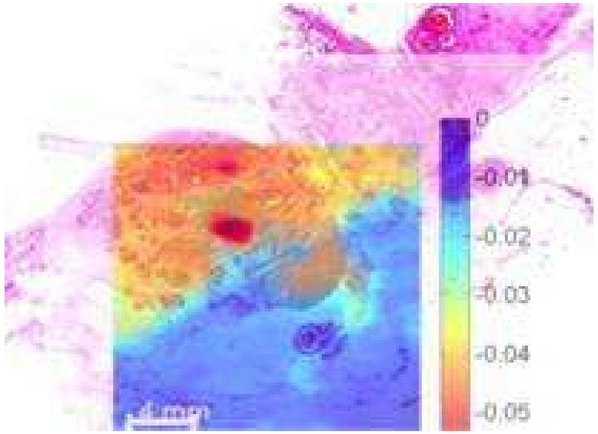
Holography
THz guiding
Interferometry

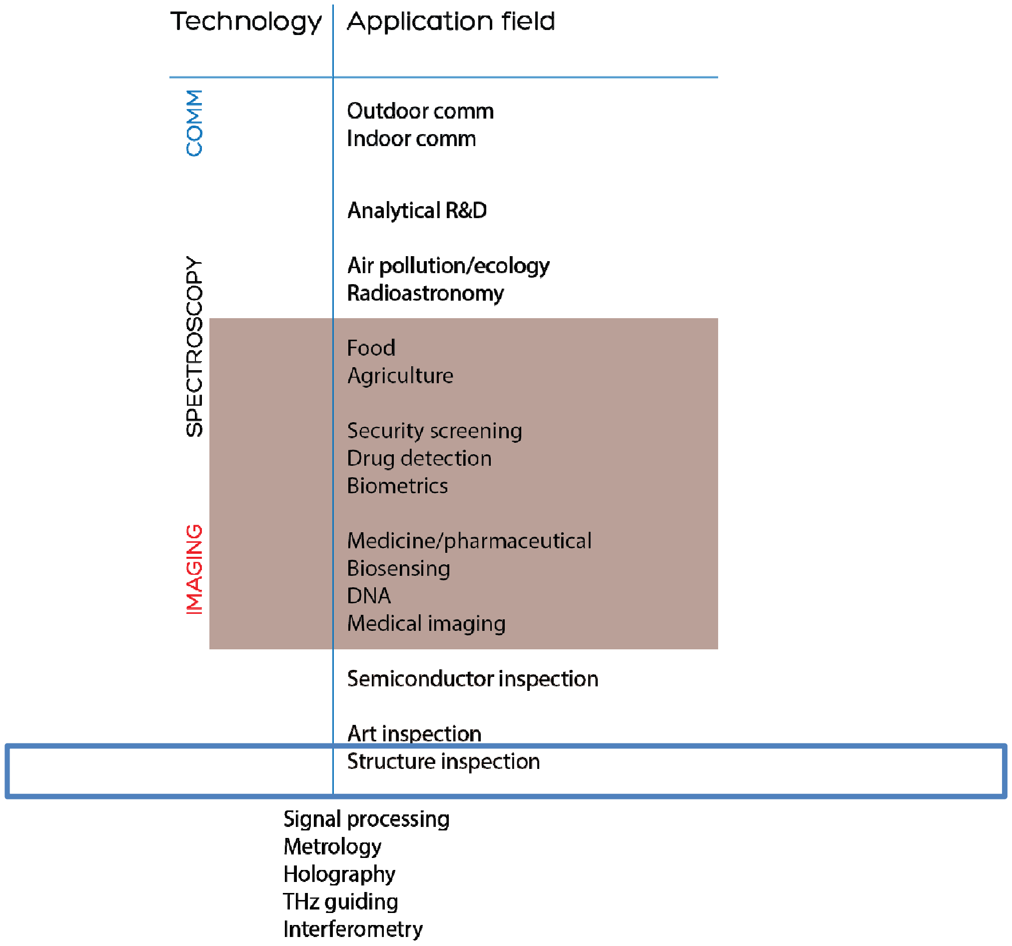
Real time breast cancer surgery

Histology and THz image overlay



Teraview, teraview.com

Applications: Inspection/Test.



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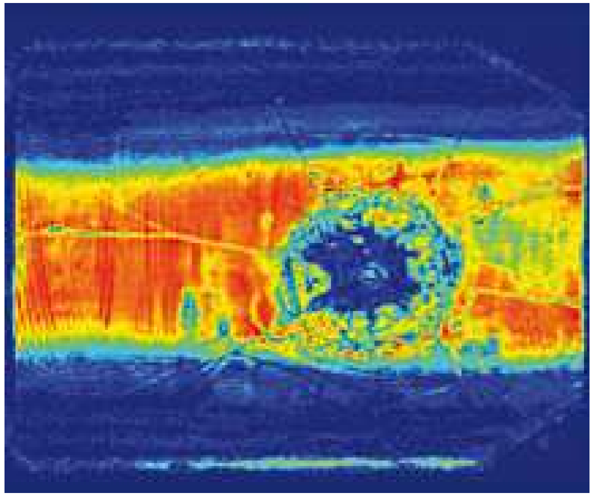
Interferometry

Kevlar inspection



Synview, synview.com

Complete Access to the mm-Wave and THz Range. Necessities

- In the last 10/20 years we have witnessed a great development in the mm-wave (Sub-THz, f<100 GHz) and THz (1THz<f<10 THz) ranges.

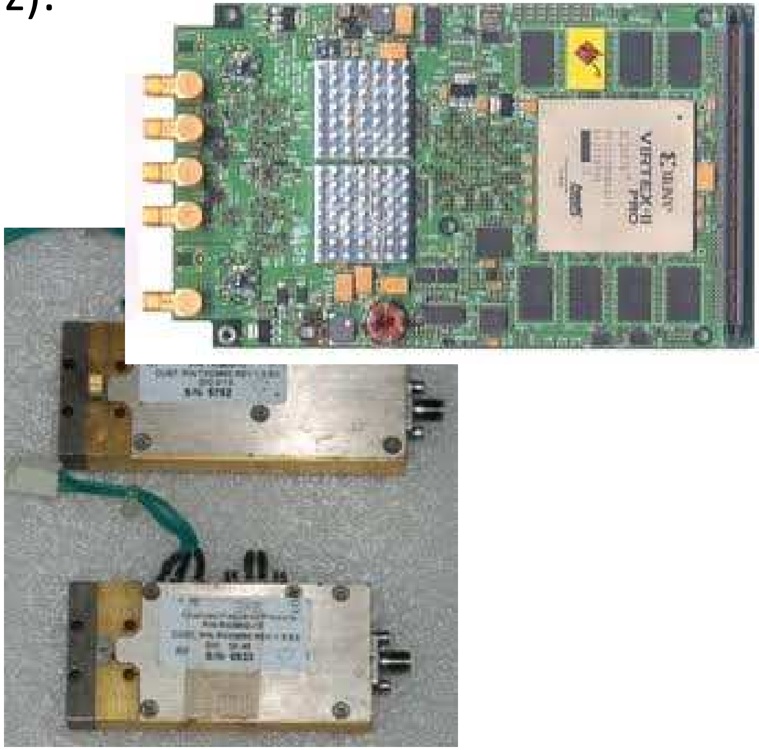
- What do we still need to really conquer these frequency ranges?

- If we look to the evolution of the neighbor frequencies (i.e. RF and Optical ranges) in the last 40 years we see that the huge development in those fields have been associated to:

    1. The development of low cost, compact and easy-to-operate-components and transceivers.
    2. Integration on a single chip/package with increasing functionalities.

Integrated Circuits and Components in the RF and Optical Ranges

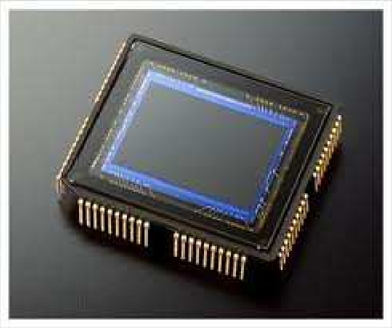
- RADIOFREQUENCY (up to several tens of GHz):

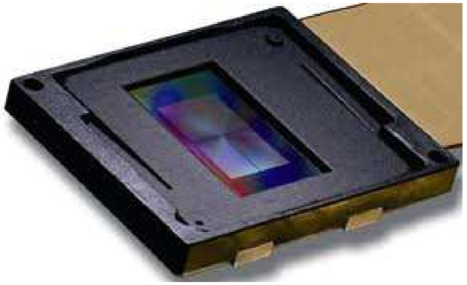


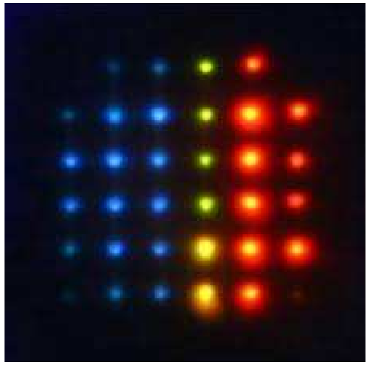
Major Driving: TELCOMUNICATIONS

Integrated Circuits and Components in the RF and Optical Ranges

- Optical Range (400 nm- 2 μm):







Major Driving: TELCOMUNICATIONS

What about the mm-wave and THz ranges?
Some Possible Strategies

- Electronic Approach:
  - Evolve the actual components in RF and low part of the mm-Wave spectrum to upper frequencies.

- Pure "Optical" Approach:
  - Use of Quantum Cascade Lasers (QCL)-based integrated transceivers (IEEE Spectrum September 2011).

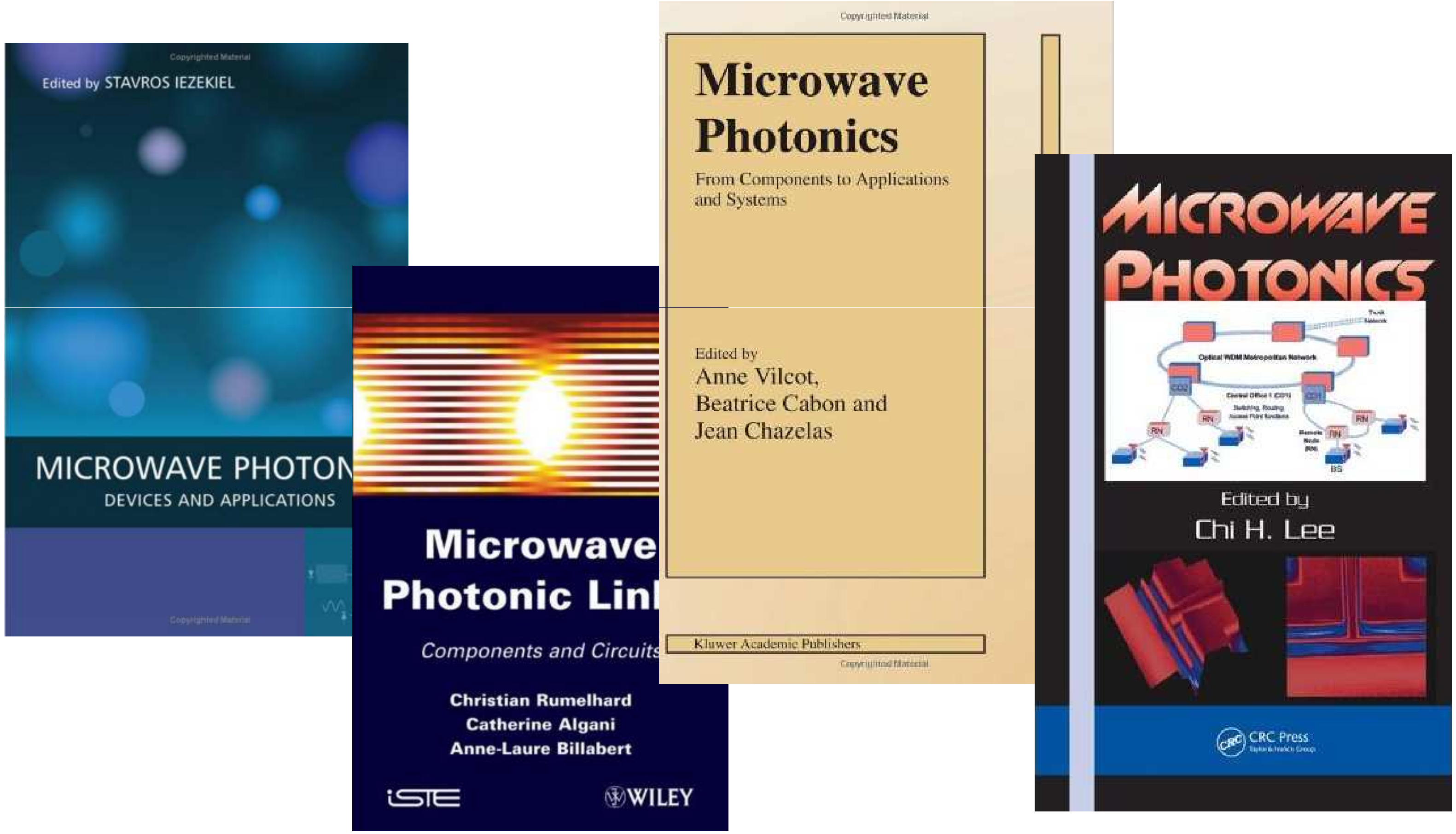
- Photonic Synthesis Approach:
  - Use of Photonic Integrated Circuits and telecommunications technology-based components to generate, detect and process mm-Wave and THz signals through photomixing of two optical wavelengths.

Why Photonic Techniques for mm-Wave and THz generation and Detection?

1.- Microwave photonics techniques.

- These are very well established techniques for microwave and RF signal transmission and processing. They are mainly based on telecom COTS components so they are becoming cost-effective solutions in many fields.
- In the last years we have witnessed an increasing interest on extrapolating these photonic generation schemes in the mm-wave and sub-THz frequency ranges. The advantages for these systems are the high quality of the signal generated and potential for compactness.

Microwave Photonics



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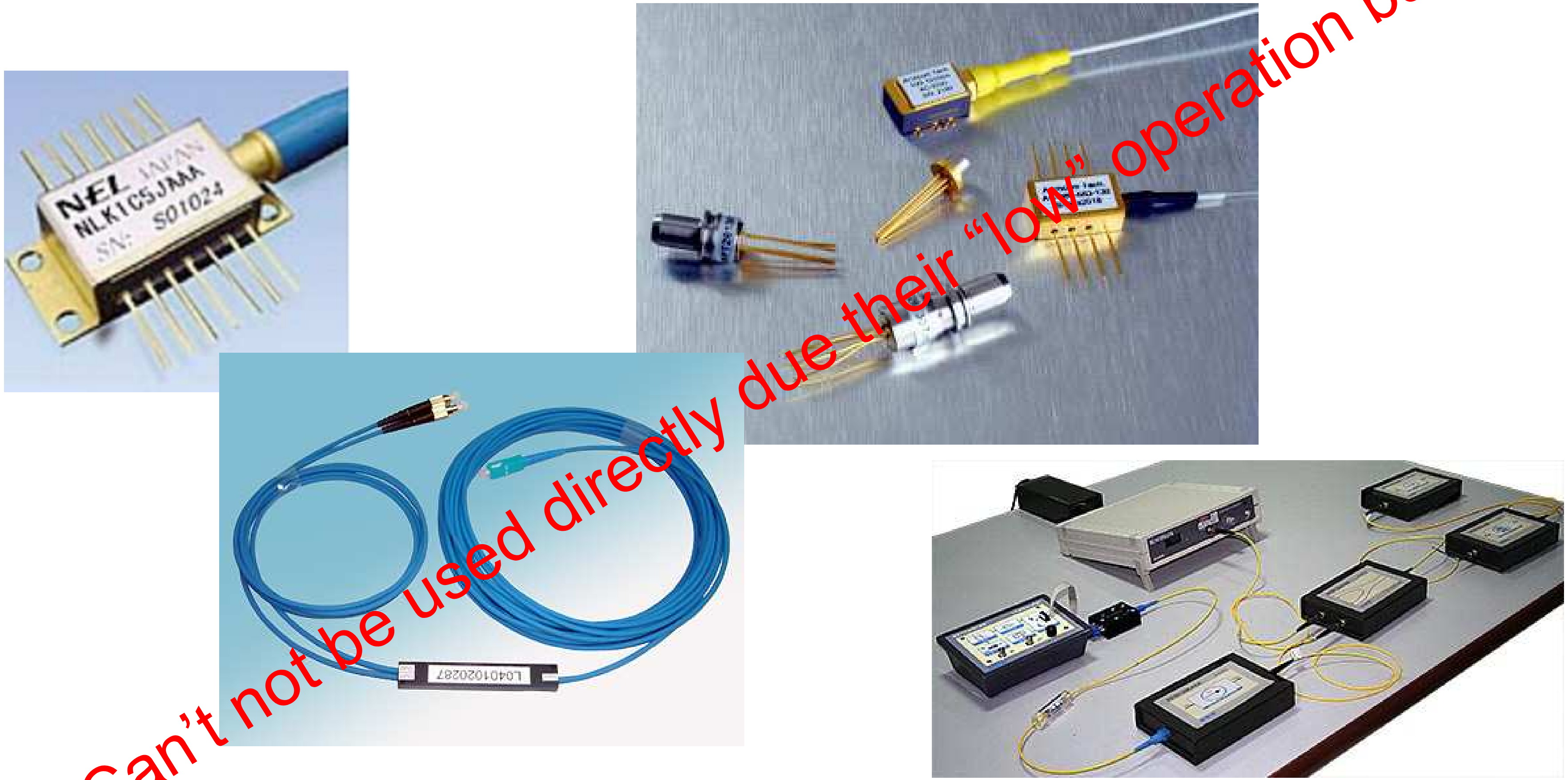
Why Photonic Techniques for mm-Wave and THZ generation?

2.- Take Advantage Telecommunication technology-based Components and Photonic Integrated Circuits.

- We can take advantage of the huge development of optical transceivers and components in the 1550 nm wavelenghts associated to the deployment of optical communications in the last 30 years.
- PICs (Photonic Integrated Circuits) are becoming a reality in this Optical Telecommunications Field. One example is the current works towards integrated OPLL for coherent detection (Coldren-UCSB) that can be directly used for photonic mm-Wave synthesis

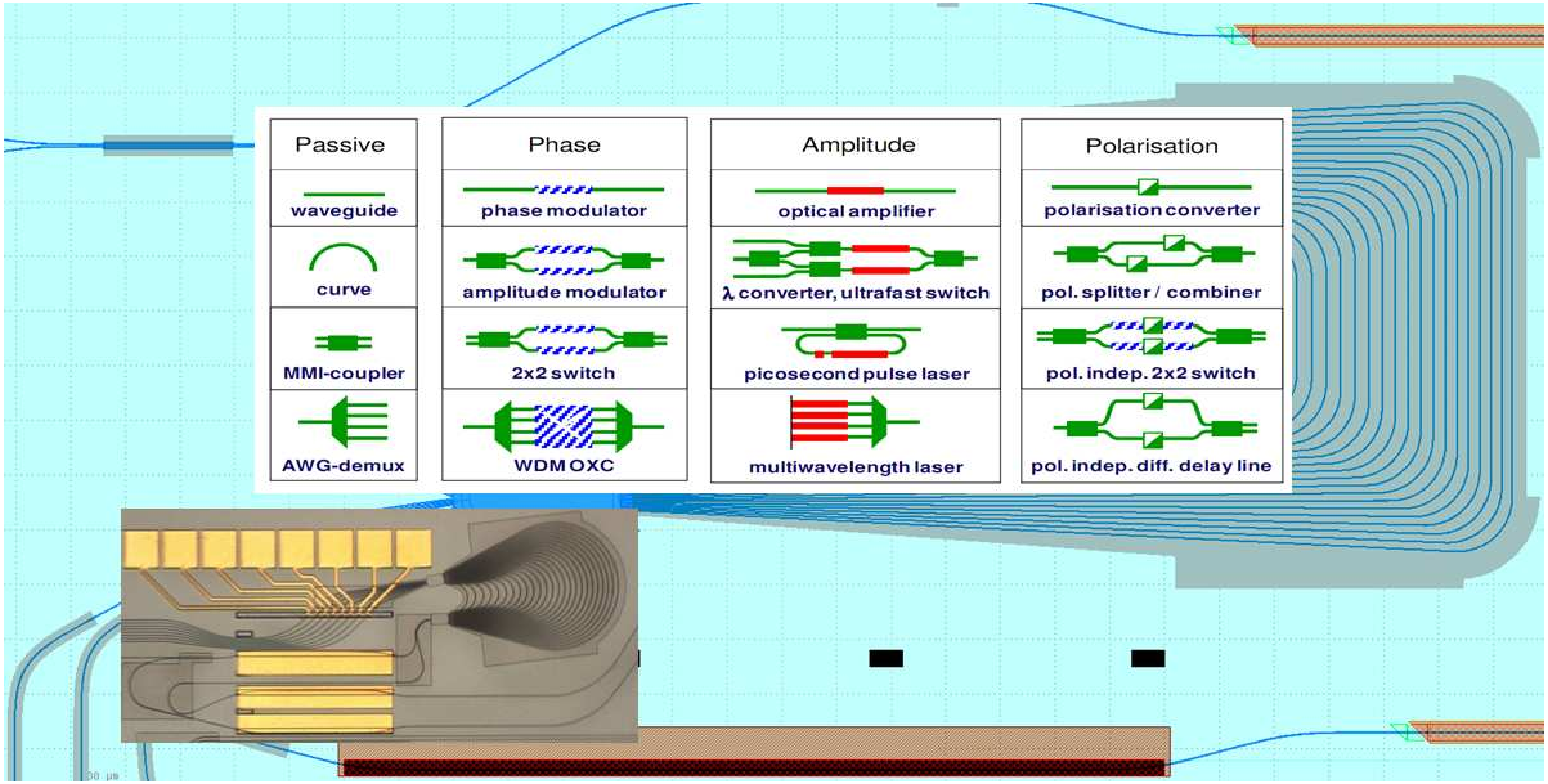
Telecommunication technology-based Components

Telecommunication technology-based Components but…..



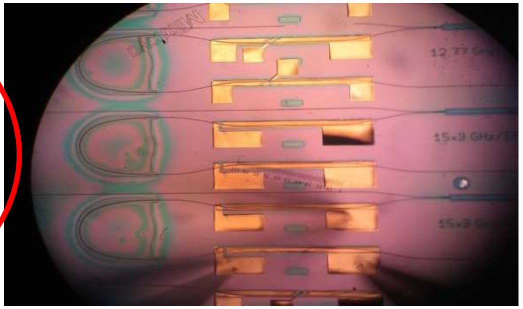
Can’t not be used directly due their “low” operation bandwidth

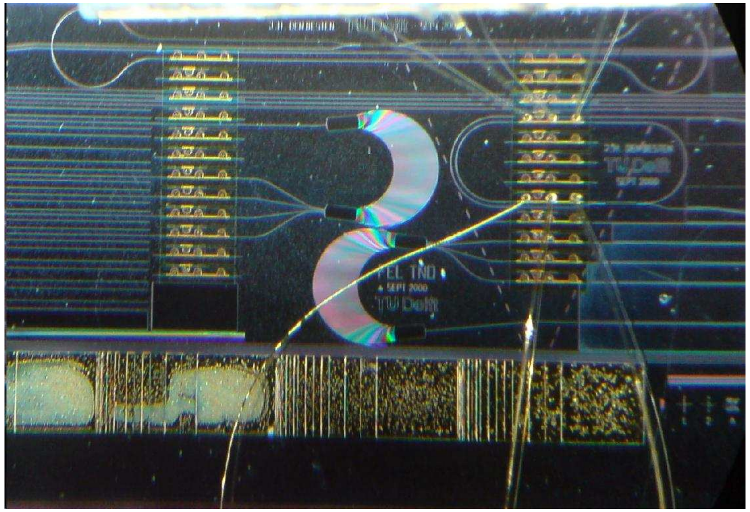
Photonic Integrated Circuits

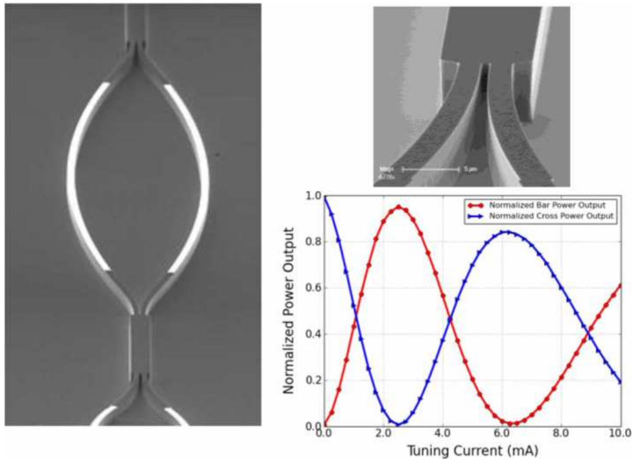


Photonic Integration Examples

Active-Passive Integration



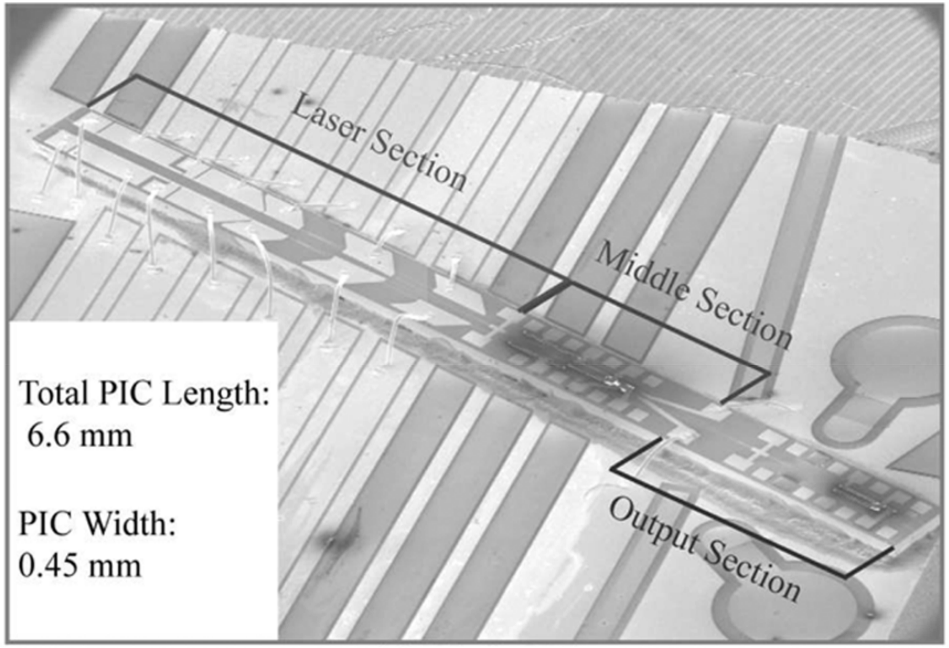


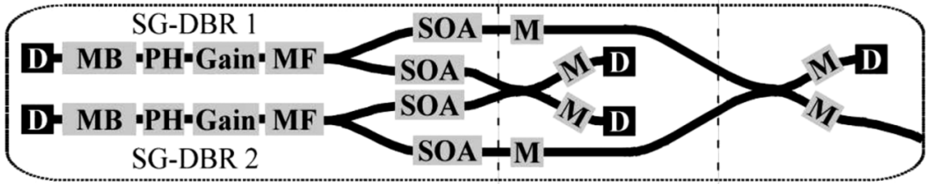


Waveguides and Mode Couplers

Arrayed Waveguide Gratings (Filtering)

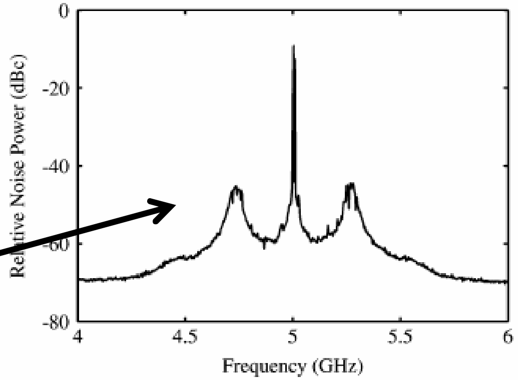
Example of complete system: OPLL





(b)

D	Photodetector/Absorber	**MB**	SGDBR Back-side Mirror
M	Modulator	**MF**	SGDBR Front-side Mirror
SOA	Semiconductor Optical Amplifier	**PH**	SGDBR Phase Section
		Gain	SGDBR Gain Section



300 MHz loop bandwidth
thanks to integration

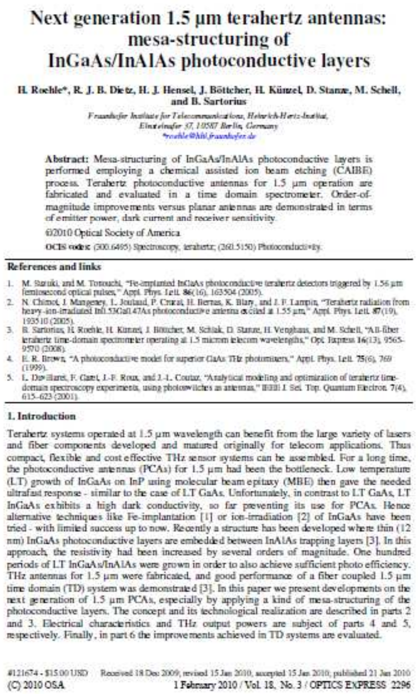
S. Ristic, A. Bhardwaj, M. J. Rodwell, L.A. Coldren and L.A. Johansson ‘An Optical Phase-Locked Loop Photonic Integrated Circuit’ Journal of Lightwave Tech., Vol. 28, Nº 4, pp. 526-537, February 2011

Why Photonic Techniques for mm-Wave and THZ generation?

3.- Take Advantage of the increasing performance of photoconductor-based and new components for THz generation and detection.

- We can take advantage of the latest developments on Uni-Travelling Carrier Photodiodes (UTC-PD), photoconductors (even a 1550 nm wavelength) and superlattice photomixers for signal generation and detection.
- Possibility of integration of such devices.

New Components with Increasing Performances



Next generation 1.5 µm terahertz antennas: mesa-structuring of InGaAs/InAlAs photoconductive layers

H. Roehle*, R. J. B. Dietz, H. J. Hensel, J. Böttcher, H. Künzel, D. Stanze, M. Schell, and B. Sartorius

Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut,
Einsteinufer 37, 10587 Berlin, Germany
**roehle@hhi.fraunhofer.de*

Abstract: Mesa-structuring of InGaAs/InAlAs photoconductive layers is performed employing a chemical assisted ion beam etching (CAIBE) process. Terahertz photoconductive antennas for 1.5 µm operation are fabricated and evaluated in a time domain spectrometer. Order-of-magnitude improvements versus planar antennas are demonstrated in terms of emitter power, dark current and receiver sensitivity.

OCIS codes: (300.6495) Spectroscopy, terahertz; (260.5150) Photoconductivity.

References and links

1. M. Suzuki, and M. Tonouchi, "Fe-implanted InGaAs photoconductive terahertz detectors triggered by 1.56 µm femtosecond optical pulses," Appl. Phys. Lett. **86**(16), 163504 (2005).
2. N. Chimot, J. Mangeney, L. Joulaud, P. Crozat, H. Bernas, K. Blary, and J. F. Lampin, "Terahertz radiation from heavy-ion-irradiated In0.53Ga0.47As photoconductive antenna excited at 1.55 µm," Appl. Phys. Lett. **87**(19), 193510 (2005).
3. B. Sartorius, H. Roehle, H. Künzel, J. Böttcher, M. Schlak, D. Stanze, H. Venghaus, and M. Schell, "All-fiber terahertz time-domain spectrometer operating at 1.5 micron telecom wavelengths," Opt. Express **16**(13), 9565-9570 (2008).
4. E. R. Brown, "A photoconductive model for superior GaAs THz photomixers," Appl. Phys. Lett. **75**(6), 769 (1999).
5. L. Duvillaret, F. Garet, J.-F. Roux, and J.-L. Coutaz, "Analytical modeling and optimization of terahertz time-domain spectroscopy experiments, using photoswitches as antennas," IEEE J. Sel. Top. Quantum Electron. 7(4), 615–623 (2001).

1. Introduction

Terahertz systems operated at 1.5 µm wavelength can benefit from the large variety of lasers and fiber components developed and matured originally for telecom applications. Thus compact, flexible and cost effective THz sensor systems can be assembled. For a long time, the photoconductive antennas (PCAs) for 1.5 µm had been the bottleneck. Low temperature (LT) growth of InGaAs on InP using molecular beam epitaxy (MBE) then gave the needed ultrafast response - similar to the case of LT GaAs. Unfortunately, in contrast to LT GaAs, LT InGaAs exhibits a high dark conductivity, so far preventing its use for PCAs. Hence alternative techniques like Fe-implantation [1] or ion-irradiation [2] of InGaAs have been tried - with limited success up to now. Recently a structure has been developed where thin (12 nm) InGaAs photoconductive layers are embedded between InAlAs trapping layers [3]. In this approach, the resistivity had been increased by several orders of magnitude. One hundred periods of LT InGaAs/InAlAs were grown in order to also achieve sufficient photo efficiency. THz antennas for 1.5 µm were fabricated, and good performance of a fiber coupled 1.5 µm time domain (TD) system was demonstrated [3]. In this paper we present developments on the next generation of 1.5 µm PCAs, especially by applying a kind of mesa-structuring of the photoconductive layers. The concept and its technological realization are described in parts 2 and 3. Electrical characteristics and THz output powers are subject of parts 4 and 5, respectively. Finally, in part 6 the improvements achieved in TD systems are evaluated.

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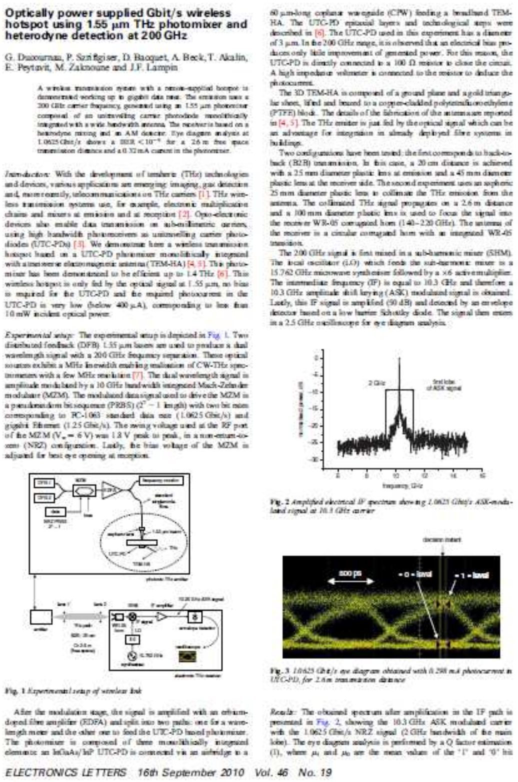
(C) 2010 OSA 1 February 2010 / Vol. 18, No. 3 / OPTICS EXPRESS 2296



Optically power supplied Gbit/s wireless hotspot using 1.55 µm THz photomixer and heterodyne detection at 200 GHz

G. Ducournau, P. Szriftgiser, D. Bacquet, A. Beck, T. Akalin, E. Peytavit, M. Zaknoune and J.F. Lampin

ELECTRONICS LETTERS 16th September 2010 Vol. 46 No. 19

JOURNAL OF APPLIED PHYSICS 109, 061301 (2011)

APPLIED PHYSICS REVIEWS

Tunable, continuous-wave Terahertz photomixer sources and applications

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[1]*Max Planck Institute for the Science of Light and University of Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[2]*Materials Department, University of California, Santa Barbara, California 93106, USA*
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(Received 4 August 2010; accepted 5 January 2011; published online 22 March 2011)

This review is focused on the latest developments in continuous-wave (CW) photomixing for Terahertz (THz) generation. The first part of the paper explains the limiting factors for operation at high frequencies ~ 1 THz, namely transit time or lifetime roll-off, antenna (R)-device (C) RC roll-off, current screening and blocking, and heat dissipation. We will present various realizations of both photoconductive and p-i-n diode-based photomixers to overcome these limitations, including perspectives on novel materials for high-power photomixers operating at telecom wavelengths (1550 nm). In addition to the classical approach of feeding current originating from a small semiconductor photomixer device to an antenna (antenna-based emitter, AE), an antennaless approach in which the active area itself radiates (large area emitter, LAE) is discussed in detail. Although we focus on CW photomixing, we briefly discuss recent results for LAEs under pulsed conditions. Record power levels of 1.5 mW average power and conversion efficiencies as high as 2×10^{-3} have been reached, about 2 orders of magnitude higher than those obtained with CW antenna-based emitters. The second part of the paper is devoted to applications for CW photomixers. We begin with a discussion of the development of novel THz optics. Special attention is paid to experiments exploiting the long coherence length of CW photomixers for coherent emission and detection of THz arrays. The long coherence length comes with an unprecedented narrow linewidth. This is of particular interest for spectroscopic applications, the field in which THz research has perhaps the highest impact. We point out that CW spectroscopy systems may potentially be more compact, cheaper, and more accurate than conventional pulsed systems. These features are attributed to telecom-wavelength compatibility, to excellent frequency resolution, and to their huge spectral density. The paper concludes with prototype experiments of THz wireless LAN applications. For future telecommunication systems, the limited bandwidth of photodiodes is inadequate for further upshifting carrier frequencies. This, however, will soon be required for increased data throughput. The implementation of telecom-wavelength compatible photomixing diodes for down-conversion of an optical carrier signal to a (sub-)THz RF signal will be required.

© *2011 American Institute of Physics*. [doi:10.1063/1.3552291]

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mm-Wave and THz Photonic Synthesis

"Disclaimer"

- When revising Photonic Generation of mm-wave and THz signal we are going to focus only on semiconductor laser sources and standard telecom components.
- For this reason, mm-wave and sub-THz photonic generation schemes using solid state (Dual Frequency Yb:KGW, Ti:Shappire) and Fiber lasers are **deliberately** omitted.

“Figures of Merit” for the Generated mm-wave and THz signals

- Power vs Frequency
- Tunability
- Quality: Phase Noise

Heterodyne Systems!!

Photonic Signal Synthesis

- Mm-Wave and Sub-THz photonic Signal Synthesis is based on heterodyning two (or more) optical modes, optical frequencies ω_1 and $\omega_{2,}$ so that $|\omega_1 - \omega_2| << \omega_1, \omega_2$ (within the photodetector bandwidth) so that:

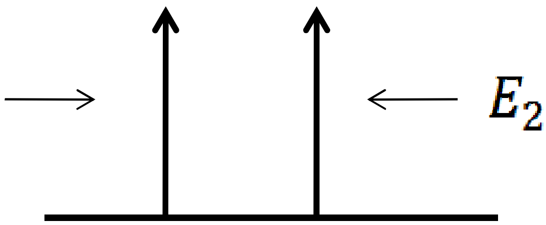
$$I_{PD} \approx < EE^* >$$

- Being E the total Optical Field at the detector input

Optical Heterodyning. Fundamentals

Optical Domain:

$$E_1 = \sqrt{P_1}\, e^{-j(\omega_1 t + \varphi_1(t))} \longrightarrow$$



$$\longleftarrow E_2 = \sqrt{P_2}\, e^{-j(\omega_2 t + \varphi_2(t))}$$

Electrical Domain:

$$I_{PD} \approx < EE^* >$$

$$I = R\left[P_1 + P_2 + 2\sqrt{P_1 P_2}\, cos\left((\omega_1 - \omega_2)t + \varphi_1 - \varphi_2\right)\right]$$

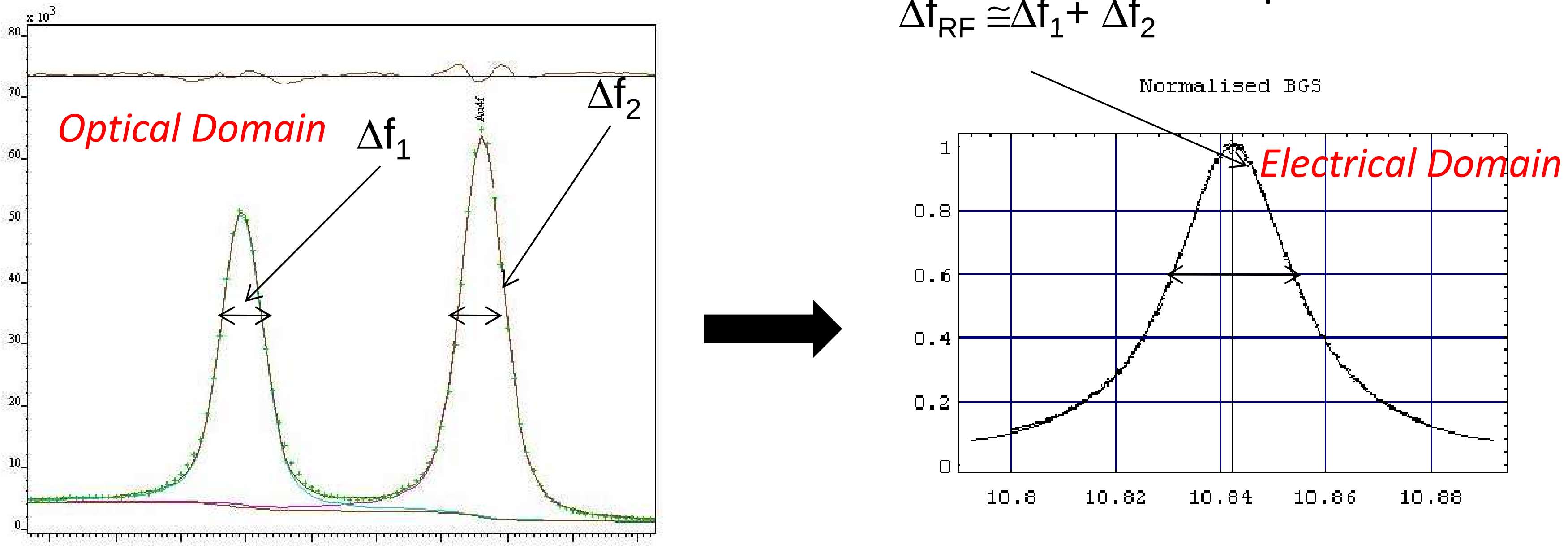
Optical Heterodyning (Free Running)

$$I = P_1 + P_2 + R\left[2\sqrt{P_1P_2}\,cos\left((\omega_1 - \omega_2)t + \varphi_1 - \varphi_2\right)\right]$$

RF component at the frequency difference

Phase relationship between the two optical modes

$\Delta f_{RF} \cong \Delta f_1 + \Delta f_2$



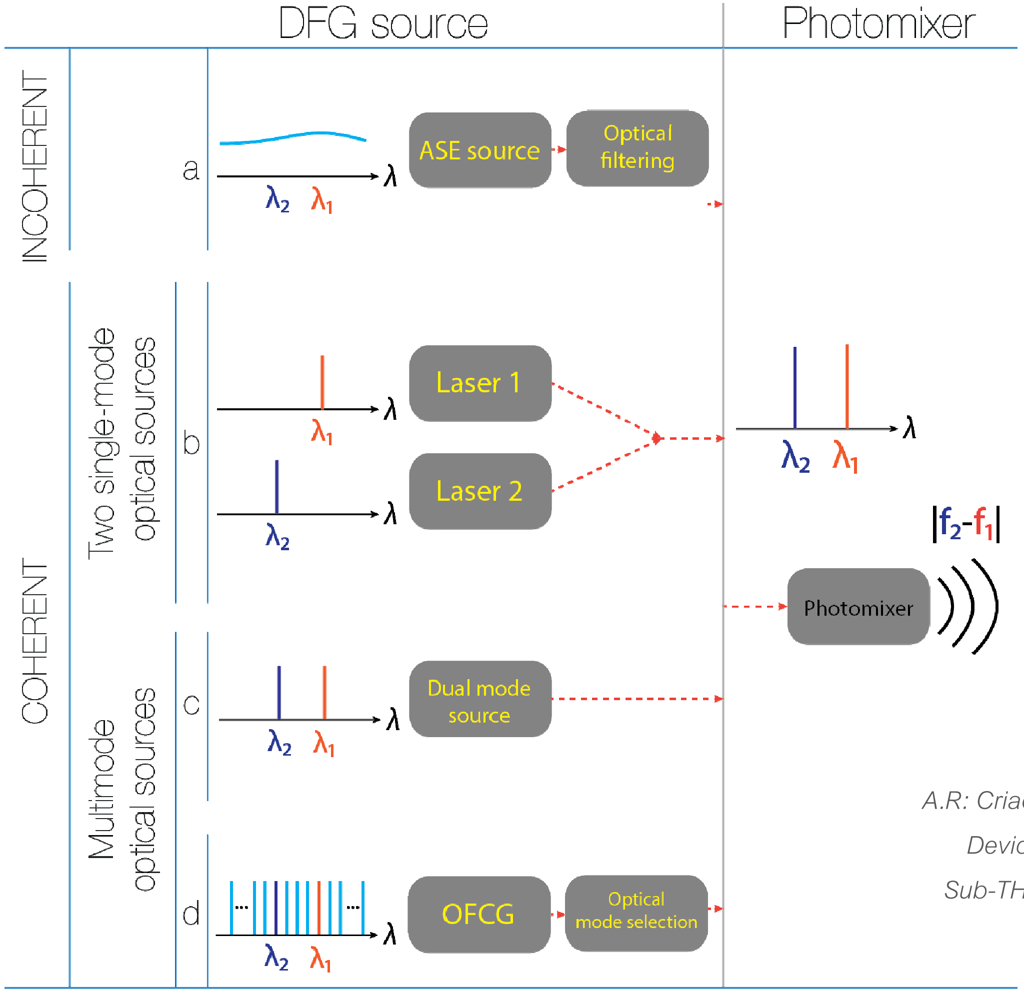
Optical Heterodyning

- If semiconductor lasers are used (efficiency and compactness) the associated linewidths can be as high as 10/50 MHz for tunable Sampled-grating DBR lasers (SG-DBR) → Very bad spectral quality of the RF generated signal
- Current and temperature influences are high (10 GHz/K and 1GHz/mA typical)→ necessity of further stabilization of the laser sources

We need to “lock” the two optical modes!!

And event better if locked to an external high-purity RF reference

Strategies for Photonic RF Synthesis



A.R: Criado: New Photonic Architectures and Devices for Generation and Detection of Sub-THz and THz wawes. PhD dissertation .Madrid 2013

Dual-Source Architectures

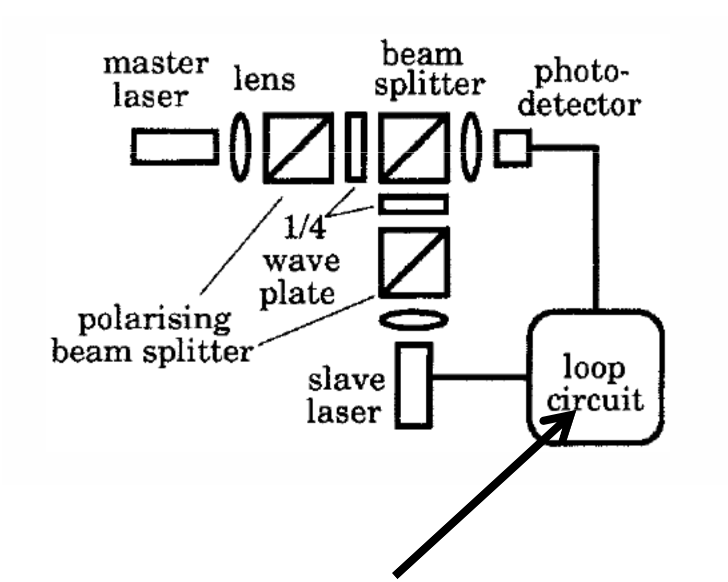
- They use two lasers (at least) so the phase noise for the two optical modes are not correlated anymore → Need of more complicated architectures.

- Tunability is possible and associated to the control loops.

- Complex systems in general

Optical Phase Locked Loops (OPLL)

They use a feedback loop to correlate the phase noise from both lasers. The loop delay has to be keep very small (ns) in order to compensate the high frequency fluctuations and not only the low frequency ones



Possible RF Reference included

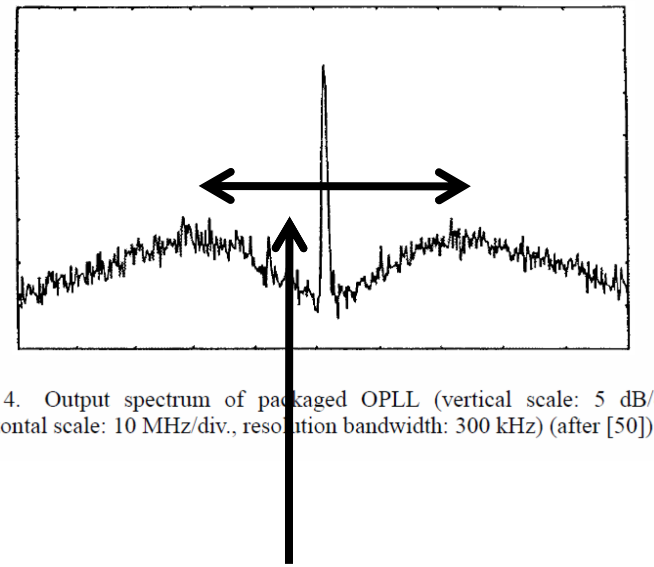


Fig. 4. Output spectrum of packaged OPLL (vertical scale: 5 dB/div., horizontal scale: 10 MHz/div., resolution bandwidth: 300 kHz) (after [50]).

Loop Bandwidth

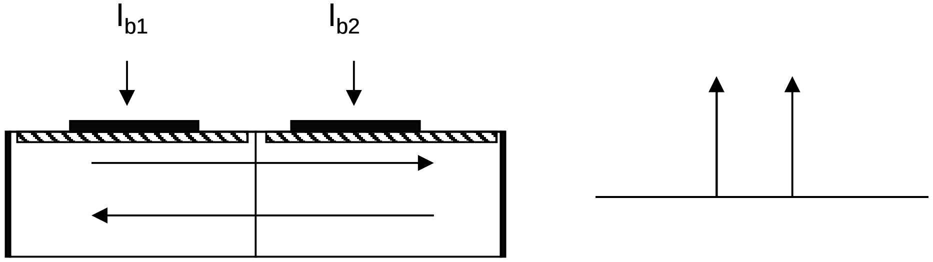
Dual-Source Architectures. Conclusions

- Tunable Photonic mm-wave and sub-THz generation possible.

- <u>However:</u>
    - Complex architectures
    - The maximum frequency difference that can be achieved is somehow limited.

Single Source
Dual-Mode Structures

- Two optical frequencies share the same laser cavity (noise correlation)
- The two-mode frequency separation is fixed by cavity parameters (physical dimensions).
- Possibility to lock to an external reference.



- Monolithic, integrated and compact devices

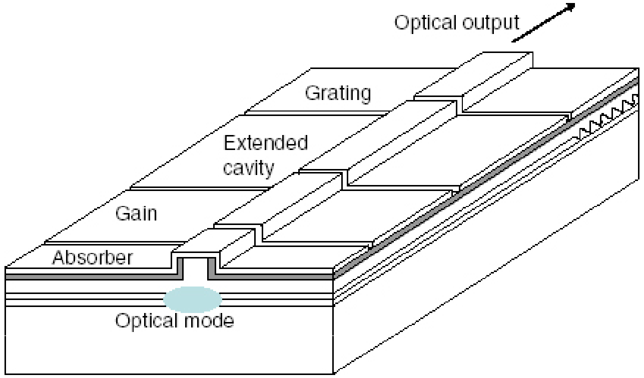
K.E. Razavi and P.A. Davies, ‘Semiconductor laser sources for the generation of millimetre-wave signals’ IEE Proceedings-Optoelectronics, Vol. 145, Nº 3, pp. 159-163. (1998)

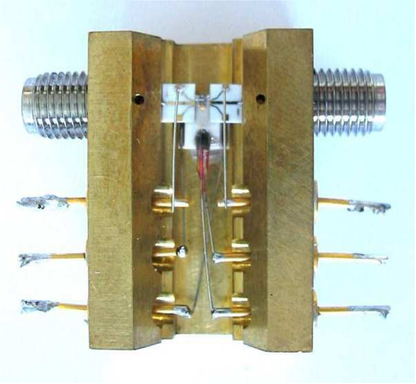
DMLL – Example of Device Structure

- Devices developed within the European Project MONOPLA.

- Structures with four sections: gain, phase, diffraction grating and saturable absorber

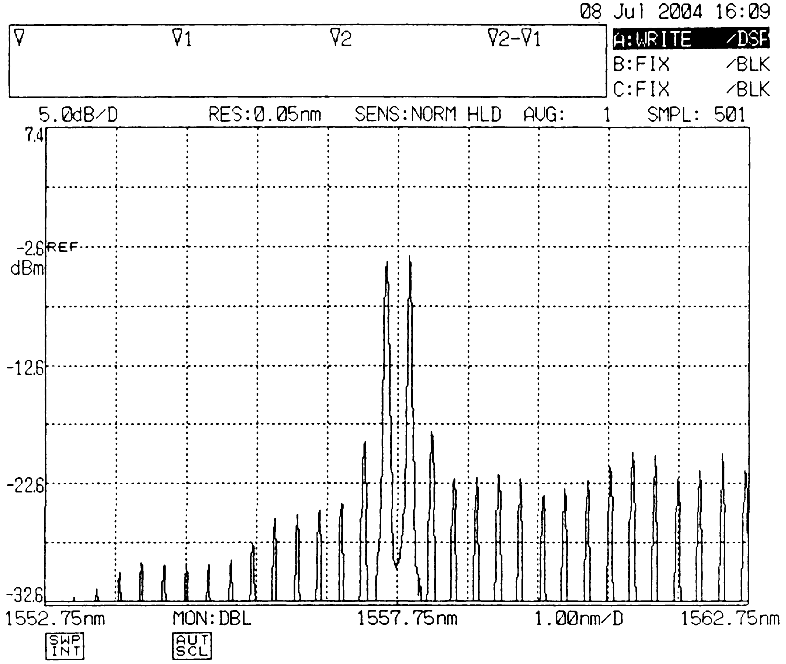
- Typical dimensions:
  - gain= 300 μm
  - phase= 370 μm
  - grating = 200 μm
  - absorber = 150 μm

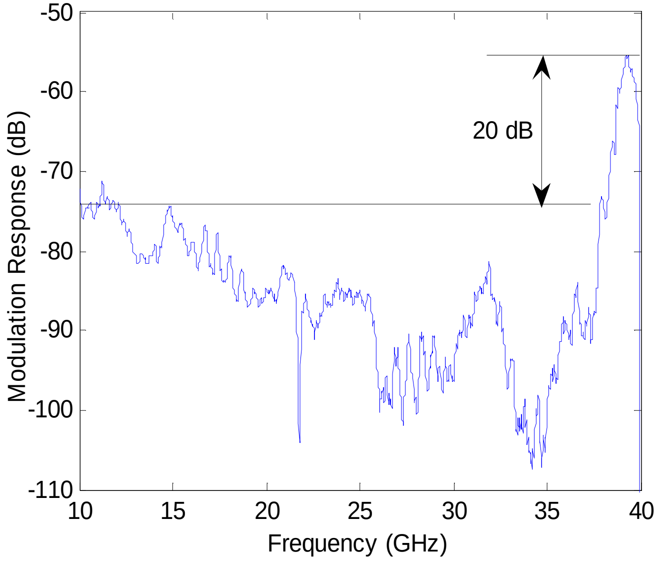




DMLL- Dual Mode Operation

- The longitudinal mode spectrum shows a two-mode behavior.
- Mode separation around 40 GHz





- A resonance peak associated to the longitudinal mode separation frequency appears in the frequency response of the device

Dual-Mode Structures. Conclusions

- Monolithic, compact devices for mm-wave photonic synthesis using a RF subharmonic reference.

- Signal processing capabilities can be incorporated (ie mixing) leading to compact and integrated systems.

- <u>However:</u>
  - Synthesized frequency fixed by physical dimensions of the cavities→ No tunable.

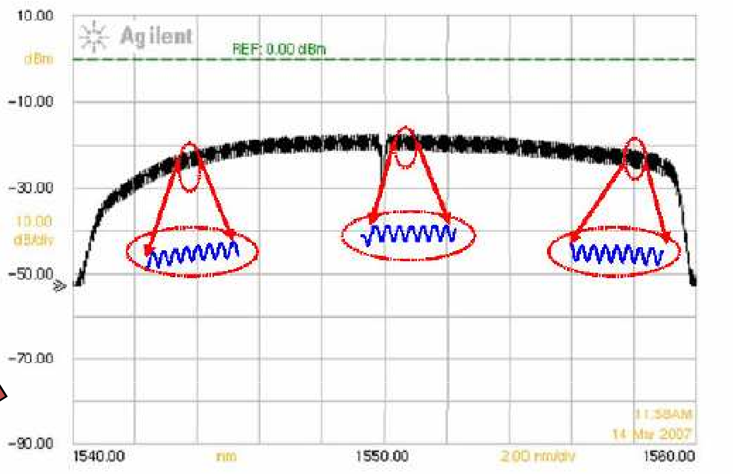
Optical Frequency Combs Generators

- As mentioned before, the photonic synthesis of mm-wave and sub-THz signals using single source schemes provide no tunability at all, while several sources architectures have their limitations associated to frequency precision and spectral purity.

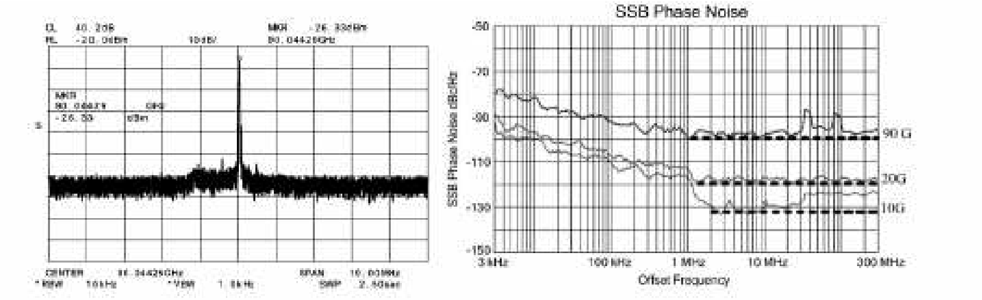
- To give the desired synthesizer performance, it will be convenient to have an optical frequency reference with high stability and known frequency difference.

Optical Frequency Combs Generators

- Optical Frequency Combs Generators (OFCG) provide such reference as are optical comb lines with frequency separation set with high precision by a microwave synthesizer.



Optical comb with over 2 THz span for 10 dB power envelope

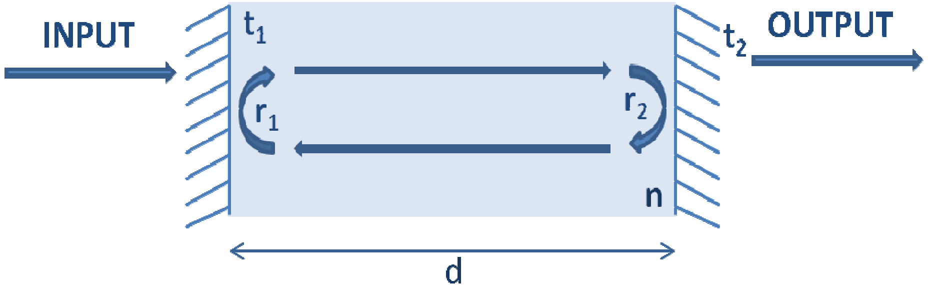


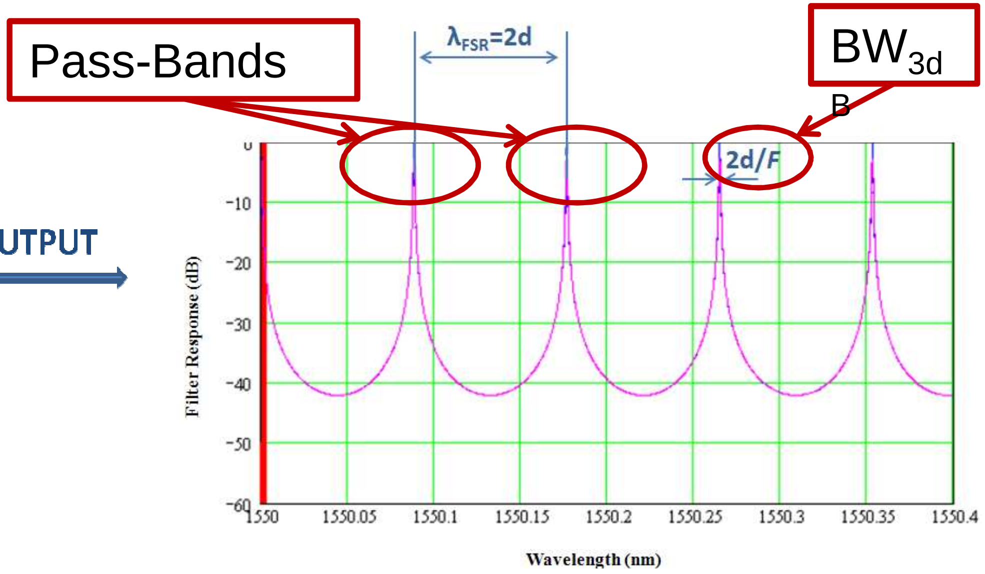
90 GHz beatnote produced by the OFCG and its measured phase noise

Mode Selection: Optical Filtering

Use of Fabry-Perot Tunable Filters.

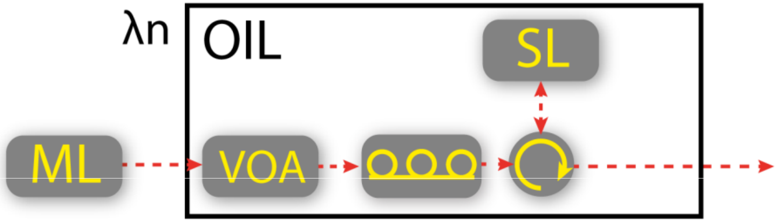
$$I_{TX} = \frac{I_{max}}{1+\left(\frac{2F}{\pi}\right)^2 \sin^2 \frac{\pi\nu}{\nu_{FSR}}}$$

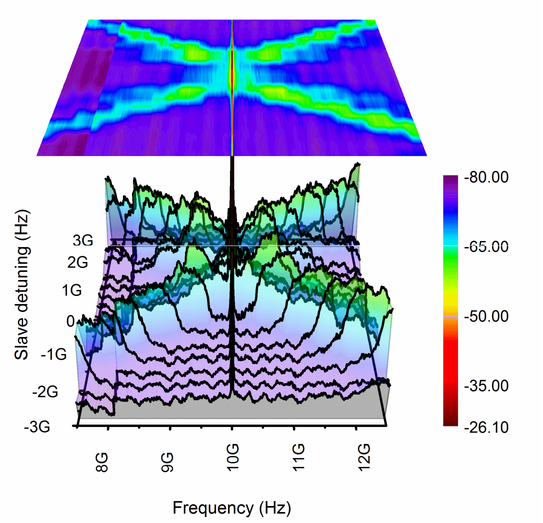


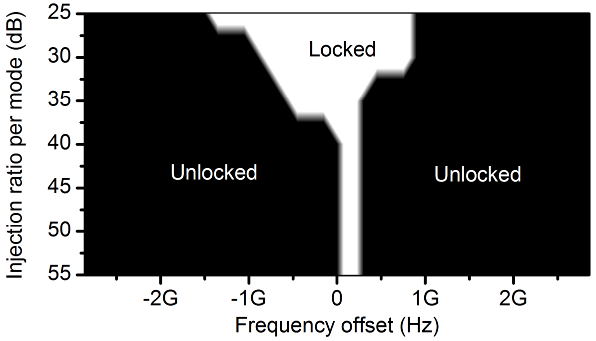


Mode Selection: Injection Locking

Two slave lasers are locked to a Master laser side-bands that is amplitude, phase modulated or coming from a comb.







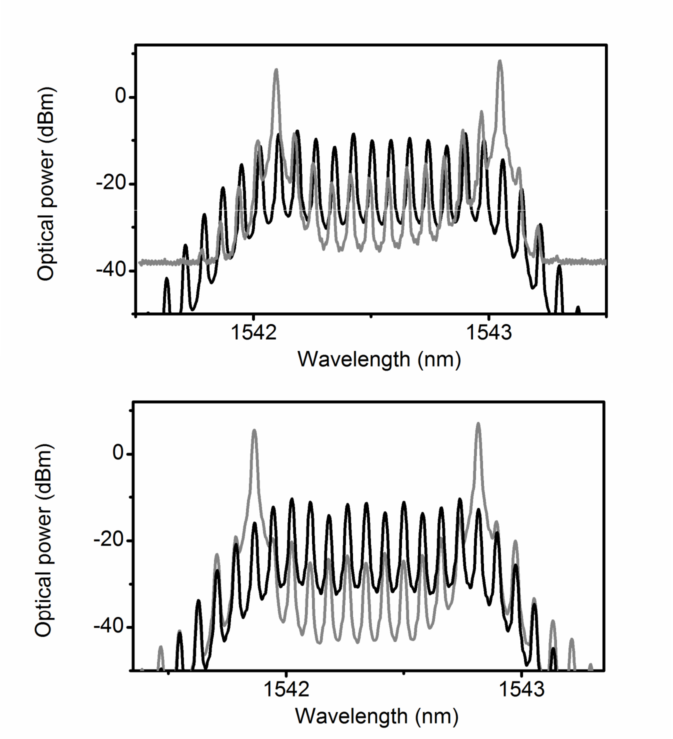
- Locking process: frequency detuning and injected power (IRm)
- Locking bandwidth

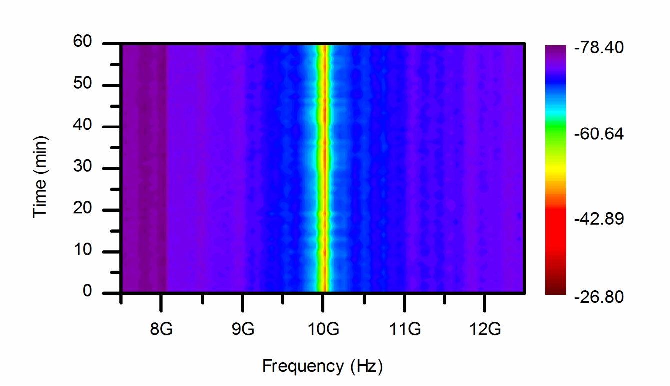
Mode Selection: Comparison

- SMSR (12 dB vs. 30 dB)
- Stability (seconds/minutes vs. hours)

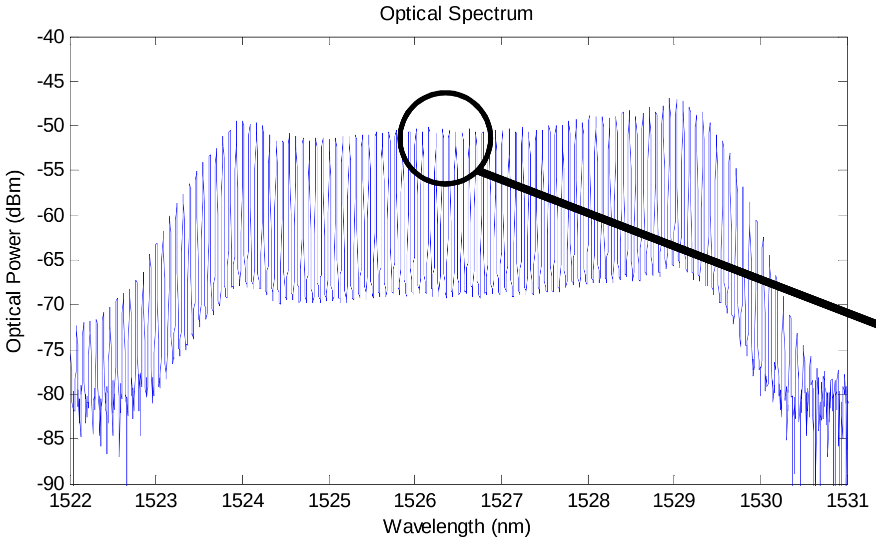
FPFT stability issues:

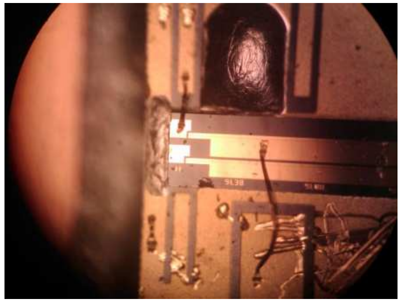
- Sensitivity of the PZT (voltage vs. wavelength, around 10 mV/10GHz)
- Drift of the filters (very long warm-up)
- Need of very accurate driving electronics and/or feedback loops

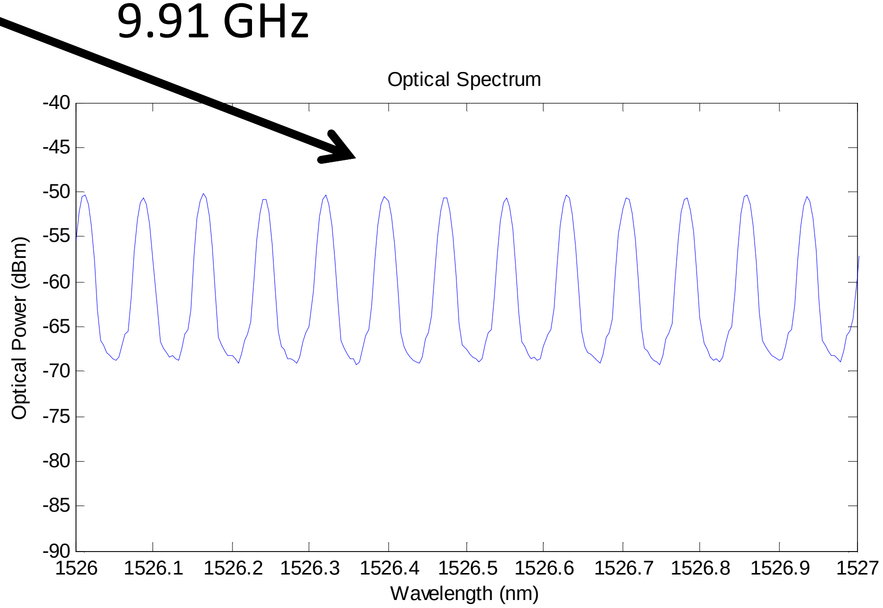




Monolithic OFCGs: Mode-locked lasers



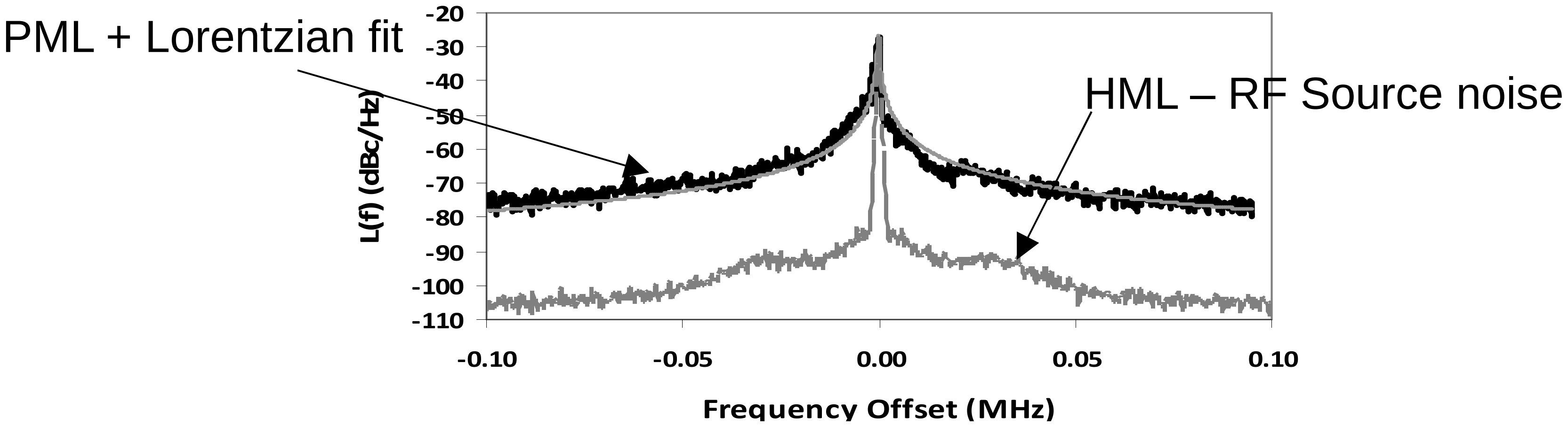




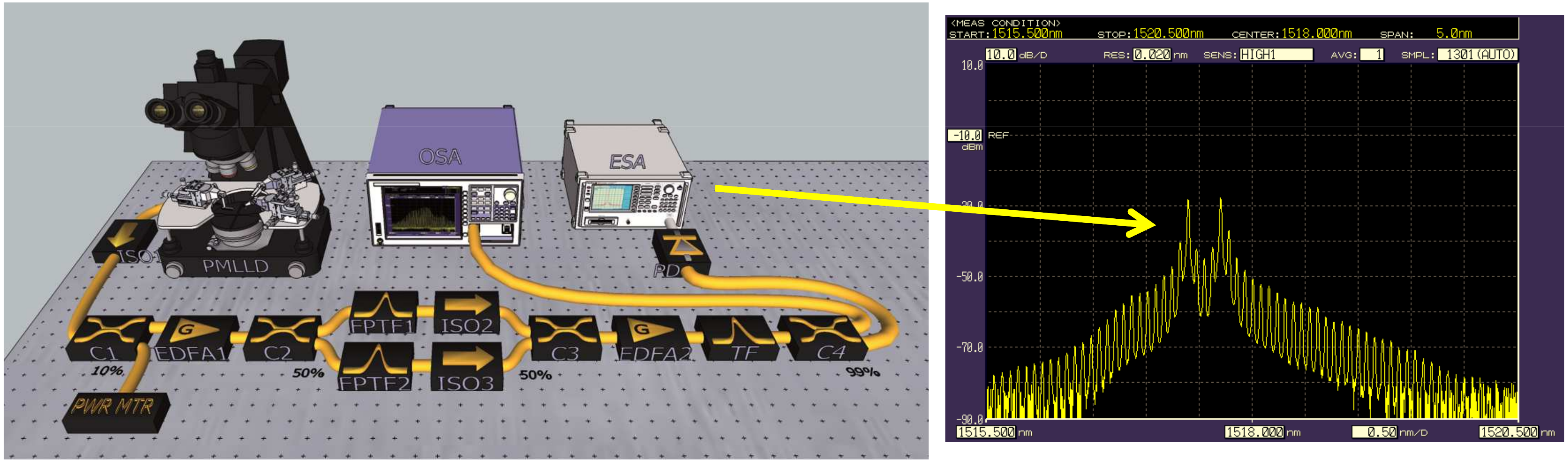
Monolithic Mode-locked lasers provide compact OFCG sources for photonic synthesis

OFCGs using Mode-locked lasers

- Passive Mode Locking
  - Low phase noise
    - Jitter: 147 fs [4MHz – 80MHz]
    - RF linewidth: < 500 Hz (narrowest to date)
- Hybrid mode locking.
    - Jitter: 74 fs [4MHz – 80MHz] – (RF source, 71 fs)
    - RF linewidth: < 10 Hz – Limited by analyzer



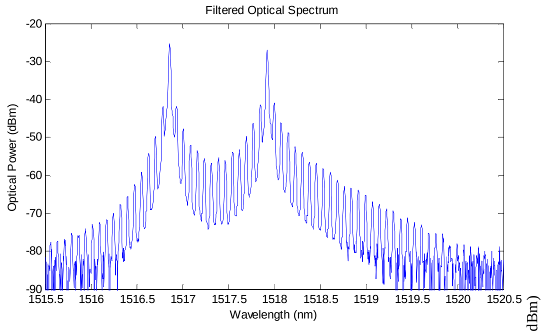
Photonic Synthesis using Monolithic OFCG and Telecom Components

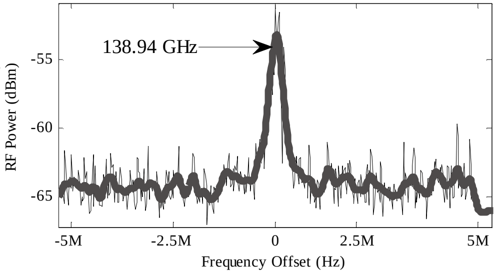


<MEAS CONDITION>
START:1515.500nm STOP:1520.500nm CENTER:1518.000nm SPAN: 5.0nm
10.0 dB/D RES: 0.020 nm SENS: HIGH1 AVG: 1 SMPL: 1301 (AUTO)
1515.500 nm 1518.000 nm 0.50 nm/D 1520.500 nm

Desired modes from the OFCG are selected using high-finesse voltage-controlled stabilized fiber filters. Further complete tunability can be achieved using external modulators

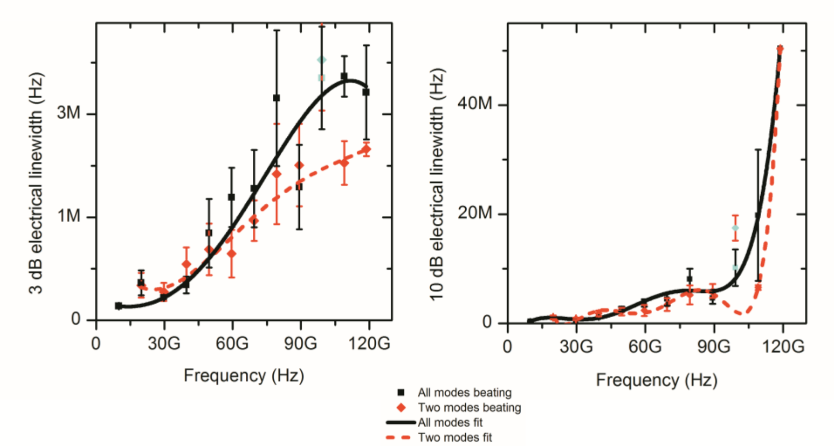
Photonic Synthesis using Monolithic OFCG and Telecom Components





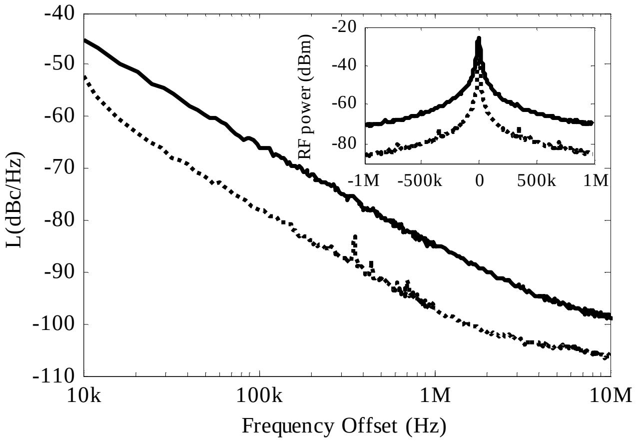
Frequencies can be synthesized on multiples of the fundamental mode separation

Reduction of the phase noise compared to all-mode beating

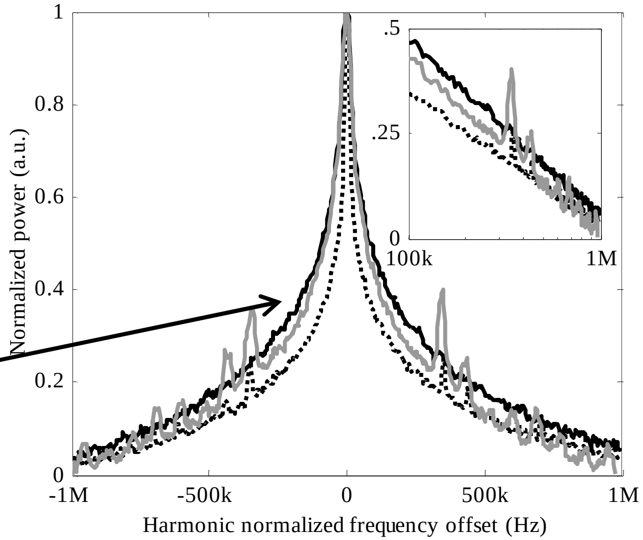


A.R. Criado; **P. Acedo**; G. Carpintero, C. de Dios; K. Yvind ‘Observation of phase noise reduction in photonically synthesized sub-THz signals using a Passively Mode-Locked Laser Diode and highly selective optical filtering’ Optics Express, Vol. 20, Nº2, pp. 1253-1260 (January 2012)

Photonic Synthesis using Monolithic OFCG and Telecom Components



Low Phase-noise of the generated mm-wave signal



No multiplication noise (20 Log(N)) compared to electronic multiplication → the synthesized signal inherits the phase noise of the fundamental frequency (the microwave reference in hybrid mode-locking

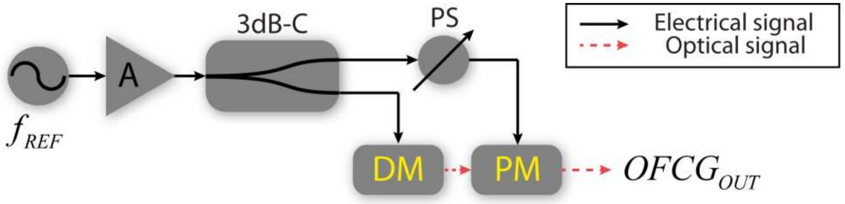
P. Acedo, G. Carpintero, A.R. Criado, C. de Dios and K. Yvind ‘Photonic Synthesis of Continuous-Wave Millimeter-Wave Signals Using a Passively Mode-Locked Laser Diode and Selective Optical Filtering’ Microwave and Optical Technology Letters Vol. 54, No. 6, pp 1416-1419 (June 2012)

Monolithic Optical Frequency Combs. Conclusions

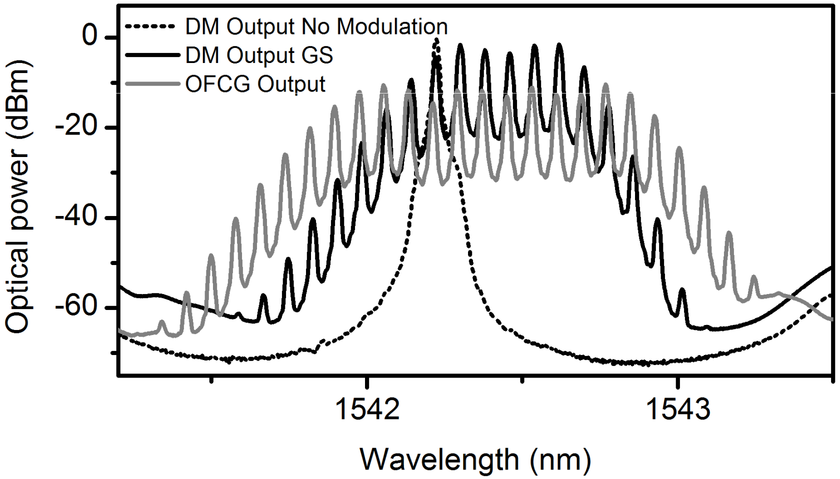
- High Quality signal generation.
- Integration capabilities (use of monolithic Mode-Locked Lasers and telecom components)

- <u>However:</u>
  - Discrete tunability (multiples of fundamental frequency)

Tunable Optical Frequency Combs



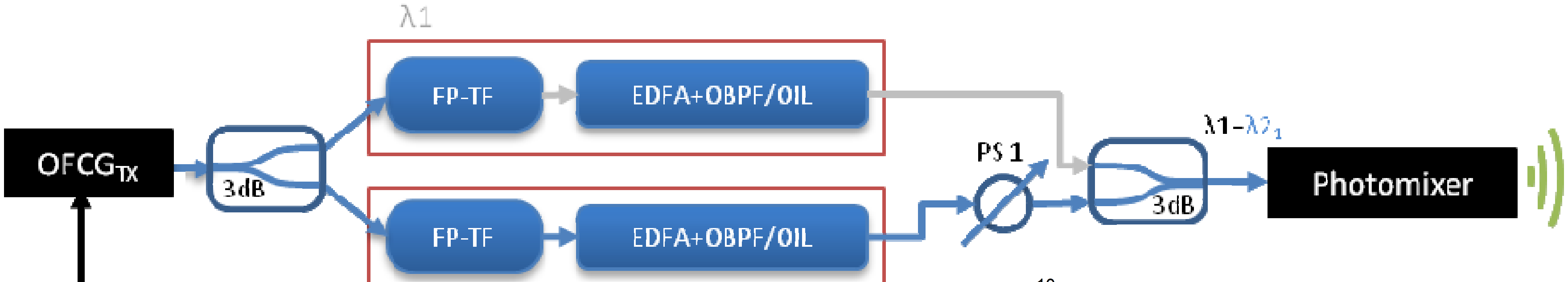
Use of a reference RF oscillator to modulate a semiconductor laser under gain-switching conditions and a Phase modulator to enlarge the optical bandwidth

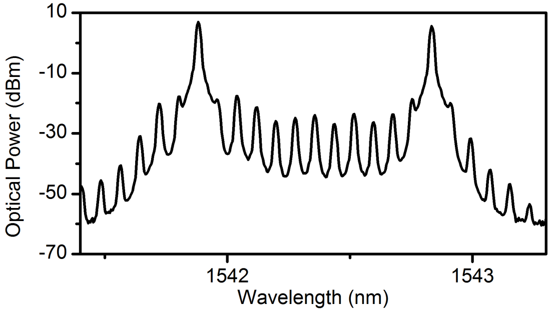


Further use of non-linear optical elements (Non-linear loops, non-linear optical fibers) would increase the bandwidth (number of modes) even more

C. de Dios, A.R. Criado, G. H. Döhler, S. Preu, S. Malzer, S. Bauerschmidt, L.E. García, **P. Acedo** and D. Segovia "Sub-THz and THz Photonic Generation with Continuous Tunability Using Gain Switching based Optical Frequency Comb Generators and n-i-p-n-i-p Superlattice Photomixers" 2012 Microwave Photonics Conference (The Netherlands-Sept 2012)

Frequency Synthesis using Tunable Optical Frequency Combs: Mode Selection



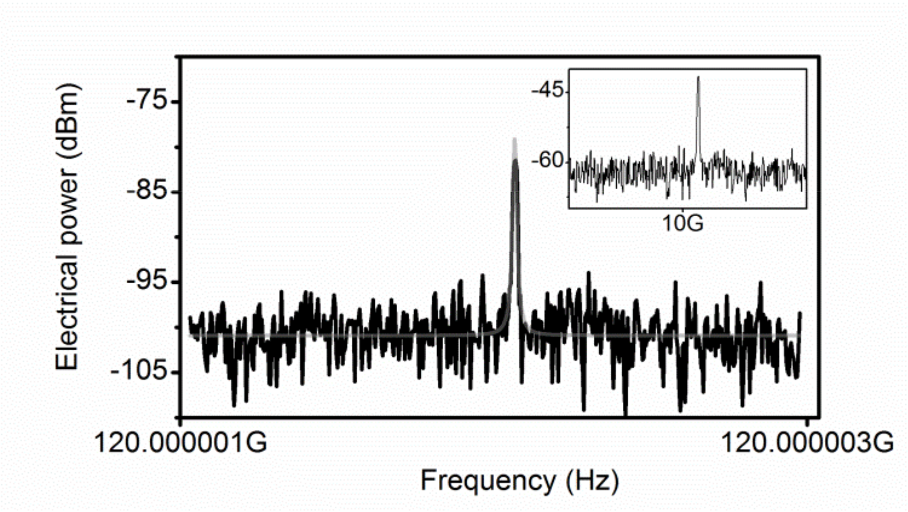


Required optical power still a issue (specially if we target photomixers arrays). Use of injection locking techniques

Á. R. Criado, C. de Dios, G. H. Döhler, S. Preu, S. Malzer, S. Bauerschmidt, H. Lu, A. C. Gossard and **P. Acedo** "Ultra narrow linewidth CW sub-THz generation using GS based OFCG and n-i-pn-i-p superlattice photomixers" Electronic Letters (Acepted for Publication, 2012)

Frequency Synthesis using Tunable Optical Frequency Combs

Ultra-Narrow Linewidth

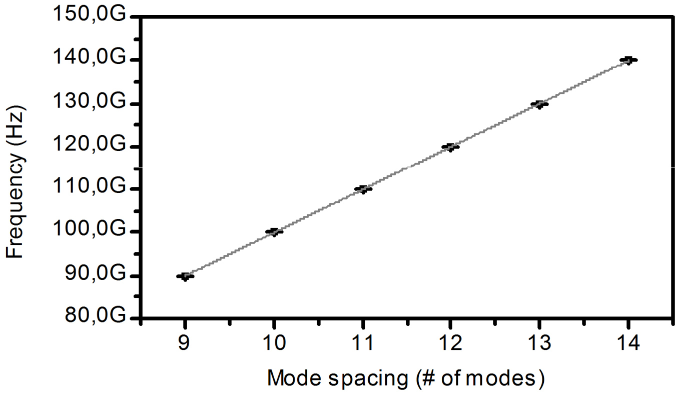


Synthesized signal at 120 GHz. Measured (black trace) and Lorentzian fit (grey trace). Inset: reference signal measured with the same dynamic range (same axis).

Á. R. Criado, C. de Dios, G. H. Döhler, S. Preu, S. Malzer, S. Bauerschmidt, H. Lu, A. C. Gossard and **P. Acedo** “Ultra narrow linewidth CW sub-THz generation using GS based OFCG and n-i-pn-i-p superlattice photomixers” Electronic Letters (Acepted for Publication, 2012)

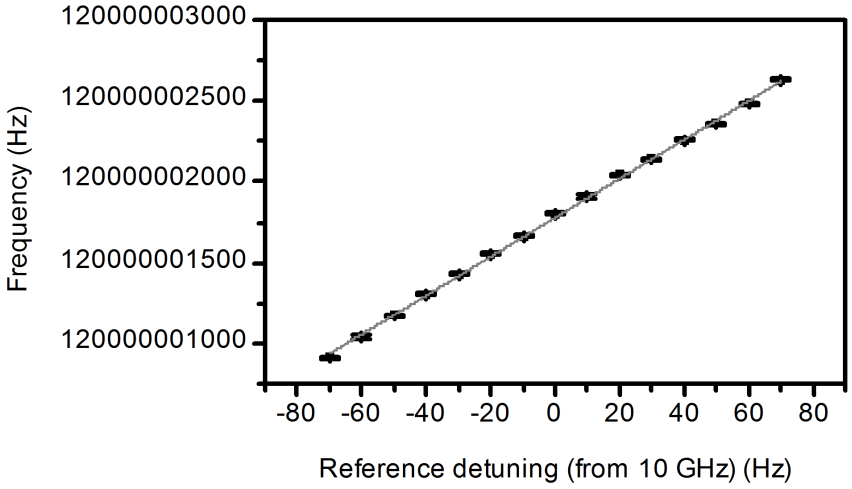
Frequency Synthesis using Tunable Optical Frequency Combs

Continous Tunability

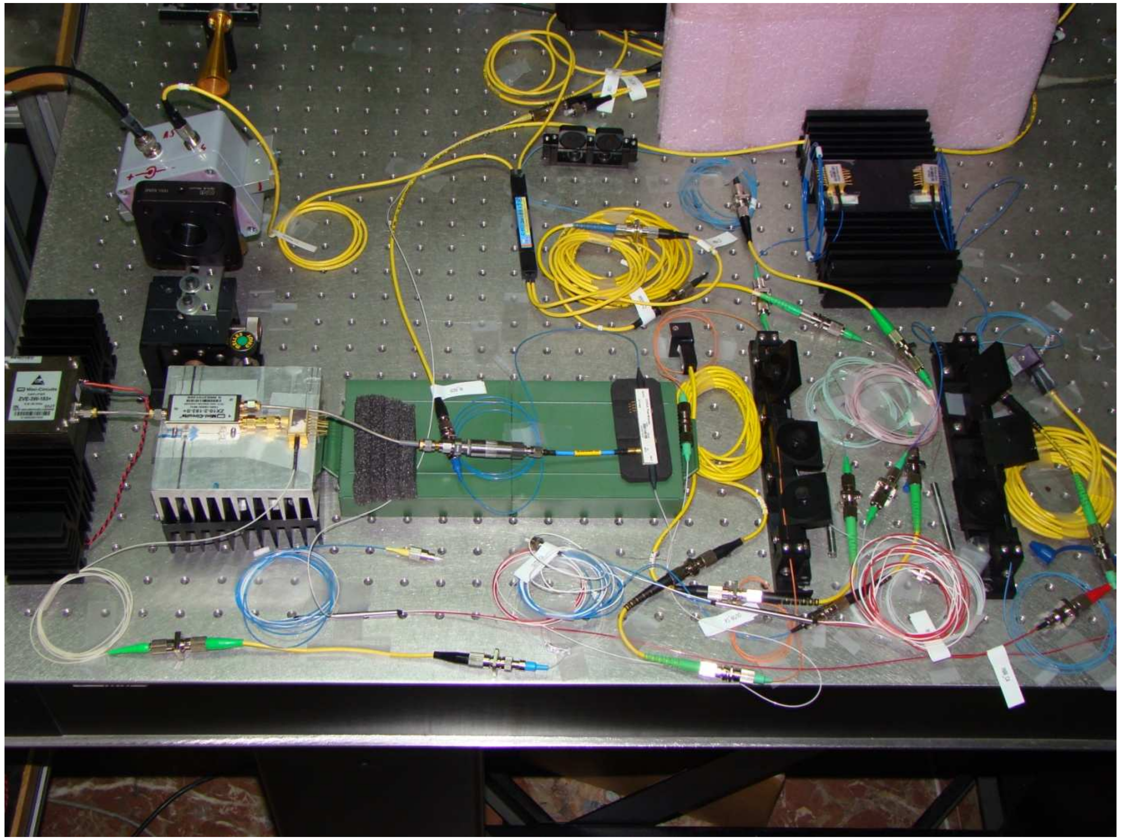


Coarse tunability (fREF=10 GHz). Measured data (average values: black dots; standard deviation: black caps); and linear fit (grey trace).

Fine tunability, 120 Hz steps (fREF=10 GHz). Measured data (average values: black dots; standard deviation: black caps); and linear fit (grey trace).



Frequency Synthesis using Tunable Optical Frequency Combs



Start-up Company

luz wavelabs

Spinoff UC3M

Microwave Photonics

Radio-over-Fiber Systems

RoF Transceivers

Terahertz

pure-T-wave

Sub-THz Photonic Generator

- FWHM <10 Hz @ 120 GHz
- Continous Tunability 0.01 Hz @ 120 GHz

www.luzwavelabs.com

What about Photomixers?

- We stated at the beginning of the talk that this photonic synthesis would work if the mm-wave/Sub-THz lays within the available BW of the photodiode/photodetector used.
- In telecom wavelengths (1500 nm) the devices typically used for mm-wave generation are:
    - TW-PD : BW ~ 100 GHz
    - UTC-PD : BW ~ 500/600 GHz

- Nevertheless there is an increasing work on LT-InGaAs and superlattice photomixers at these wavelengths although so far it is been difficult to achieve performances approaching that of LT-AsGa in 850 nm

State of the Art for UTC-PDs

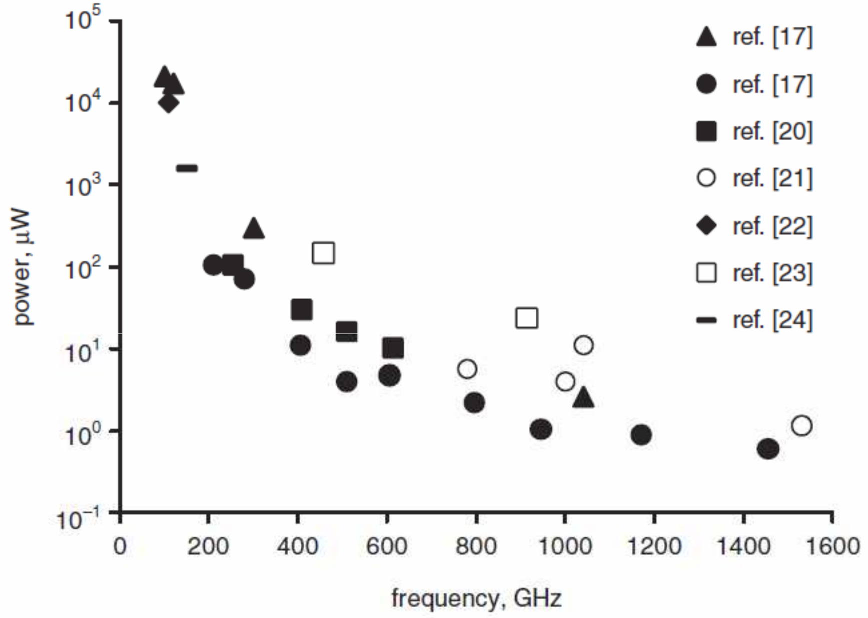
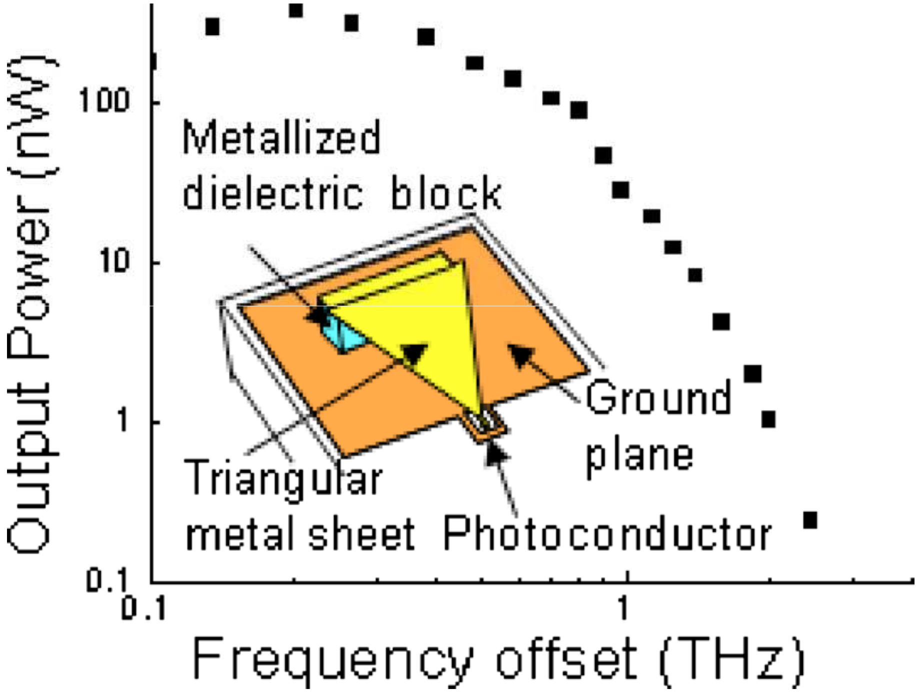


Fig. 2 *THz power generated by OHG at different frequencies*

Open symbols, narrowband antennas; filled symbols, broadband antennas

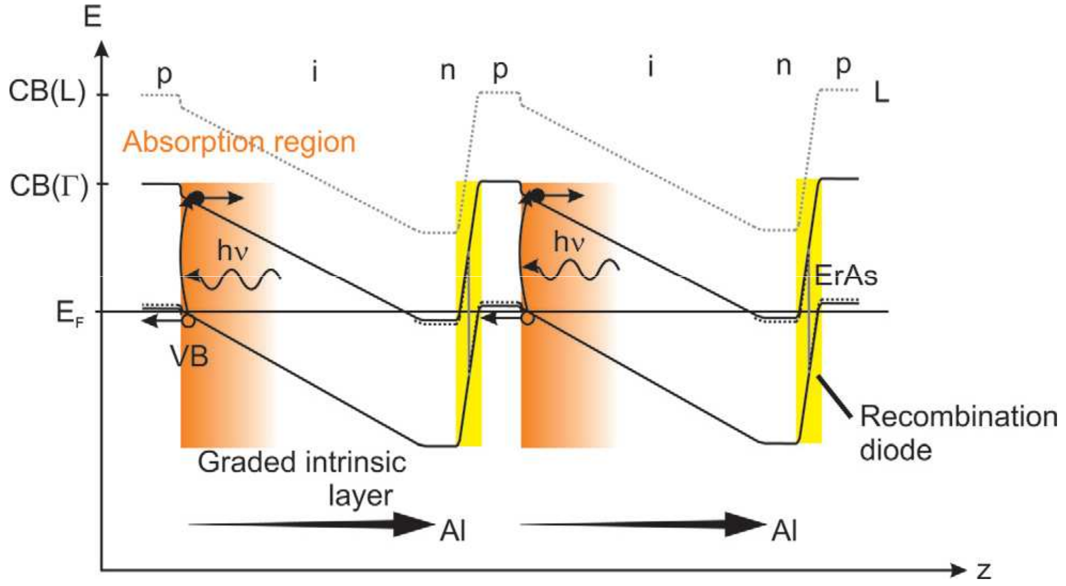
M.J. Fince, E. Rouvalis, L. Ponnampalam, C.C. Renaud and A.J. Seeds ‘Telecommunications technology-based terahertz sources’ Electronics Letters, Special Supplement on Terahertz Technology , pp. S28-S31, December 2010

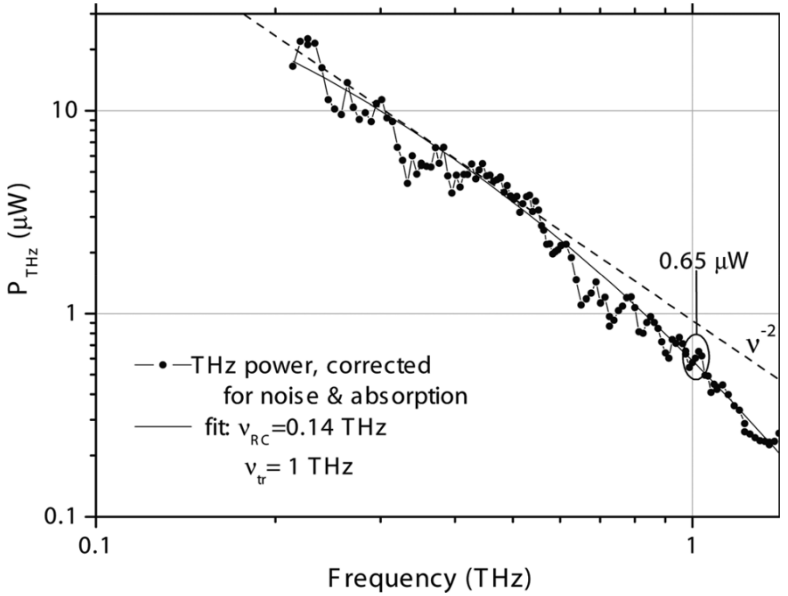
State of the art for Photomixers @ 1.55 micron



J. Mangeney, F. Meng, D. Gacemi, E. Peytavit, J. F. Lampin, and T. Akalin 'Terahertz generation and power limits in In0.53Ga0.47As photomixer coupled to transverse-electromagnetic-horn antenna driven at 1.55 um wavelengths' Applied Physics Letters, Vol. 97, Nº 16 (161109) 2010

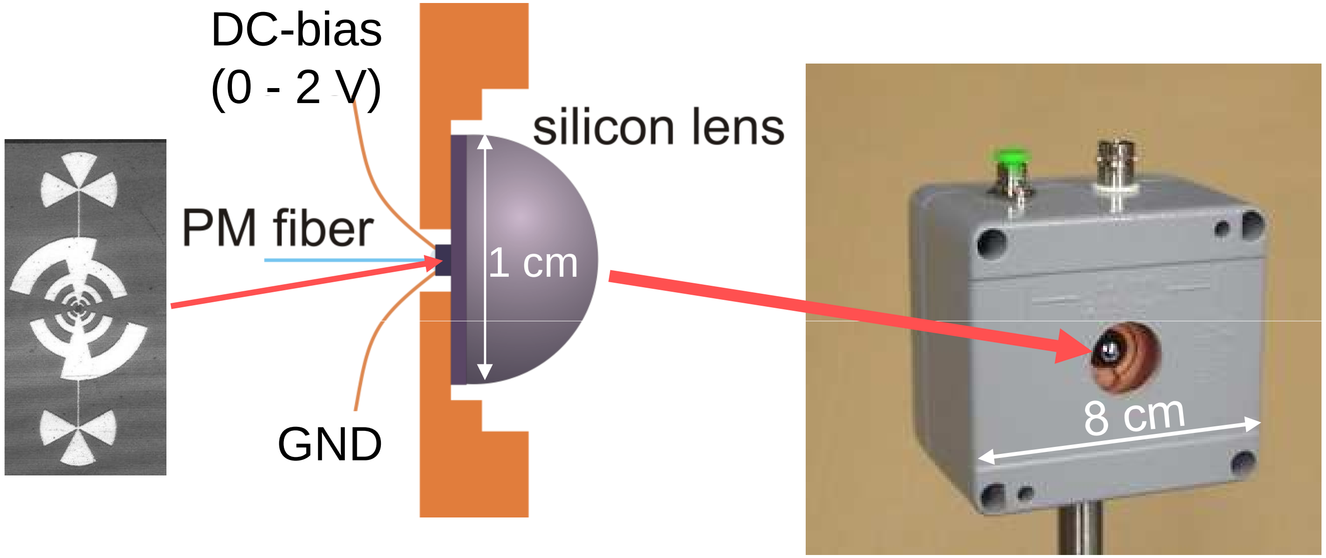
Superlattice (nip-nip)Photomixers

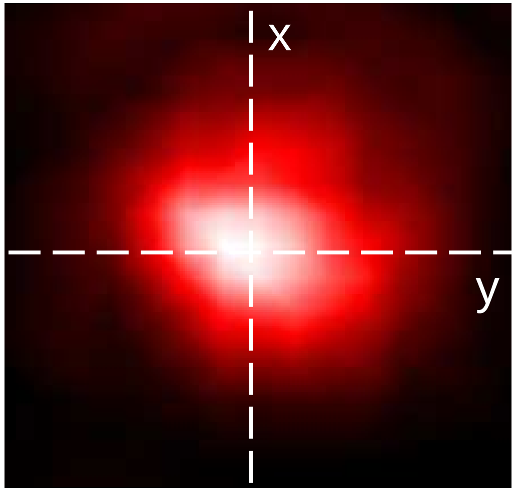


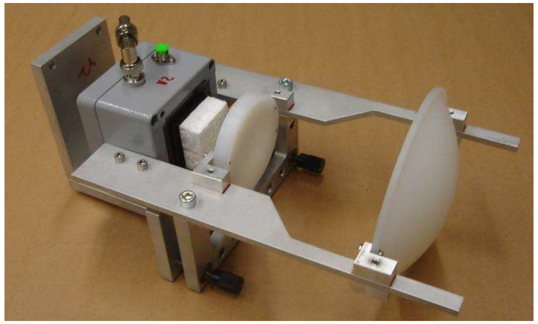


S. Preu, G. H. Dohler, S. Malzer, L. J. Wang and A. C. Gossard 'Tunable, continuous-wave Terahertz photomixer sources and applications' Journal of Applied Physics, Vol. 109, Nº6 (061301) 2011

Tunable, Continuous -Wave Photomixer–based sources

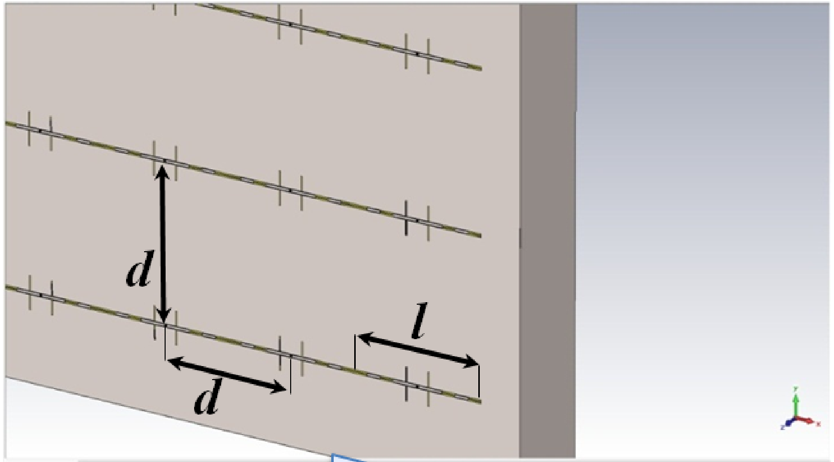






S. Bauerschmidt, S. Preu, S. Malzer, G. H. Döhler, L. J. Wang, H. Lu, and A. C. Gossard, “Continuous wave Terahertz emitter arrays for spectroscopy and imaging applications”, Proc. SPIE Vol. 7671, 76710D-1 (2010)

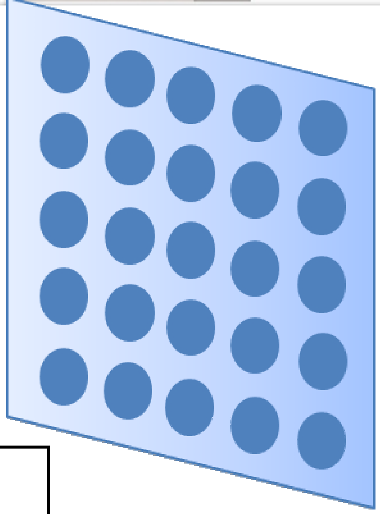
Photomixer arrays



- 50mW optical power for each element.
- 5X5 Array Antenna.
- Total optical power = 1.25 W

- The array antenna is equipped with an array of Silicon Microlens suitable in dimension and well aliened to focus the radiation at a single focal plane.

5X5 Silicon Microlens array



S. Al-Daffaie, **P. Acedo, H. Hartnagel** ‘Simulation of a CW THz Camera Scheme’ WOCSDICE 2012. Porquerolles (France) 2012

Photomixers: Conclusions/Future trends

- In the last years great advantages have been reported on photomixers and photoconductors @ 1550 delivering more and more power up to the lower THz band (up to 2 THz).

- Moreover, different strategies have been also proposed to increase the generated power and THz frequencies:
  - Photoconductor arrays
  - Large Area Emitters

mm-Wave and THz Photonic Processing

Phase Control in the Optical Domain

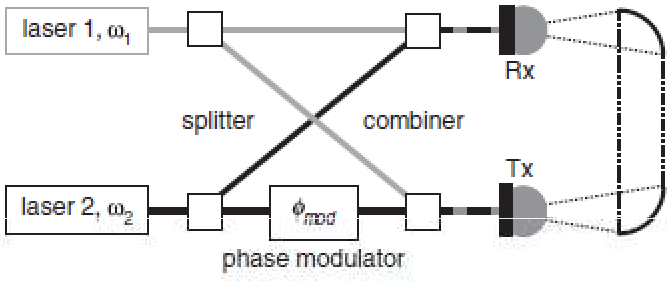


Fig. 2 *Modified CW THz system*

Optical phase modulator replaces both mechanical delay stage and chopper

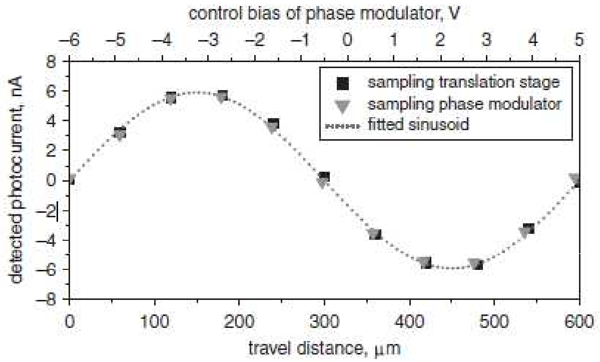


Fig. 3 *Sinusoids of detected signal, recorded at frequency of 500 GHz with mechanical delay stage (see Fig. 1) and electro-optic modulator (see Fig. 2)*

T. Göbel, D. Schoenherr, C. Sydlo, M. Feiginov, P. Meissner and H.L. Hartnagel, 'Continuous-wave terahertz system with electro-optical terahertz phase control' Electronics Letters Vol. 44 No. 14 (2008)

THz Pulse Shaping

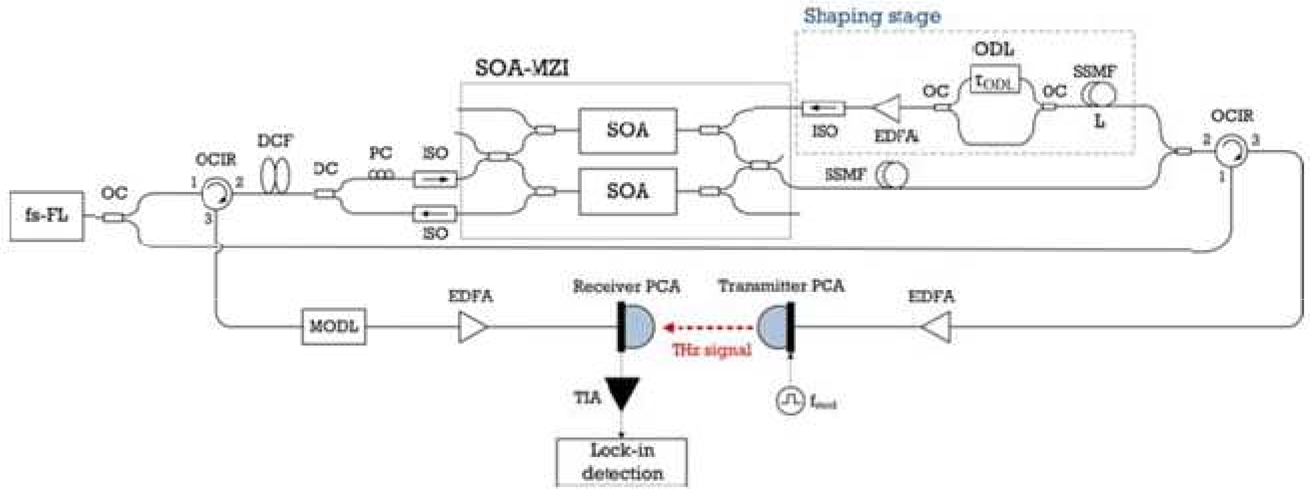


Fig. 2. Optical pulse shaper integrated in a fiber-based THz-TDS system.

Jesús Palací, Alexander Bockelt and Borja Vidal, 'Terahertz radiation shaping based on optical spectrum modulation in the time domain' Opt. Express, Vol. 20, No. 21, pp. 23117-23125, (2012)

Processing: Conclusions/Future trends

- Processing of THz signal in the optical domain possible.

- Direct extrapolation of the microwave photonics techniques already developed for “low” frequencies (GHz).

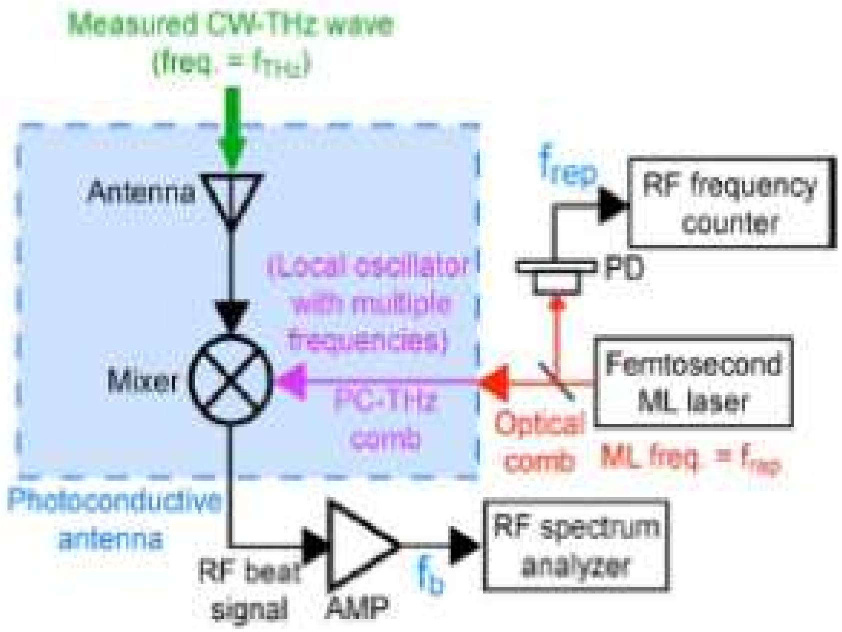
- Full access to this technologies and component will allow the implementation of more and more complex systems with increasing functionalities.

mm-Wave and THz Photonic Detection

“Disclaimer”

- The use of photomixers for the detection of THz signals is more than 20 years old now. Photomixers are illuminated with two wavelenghts at the desired separation and a DC voltage appears if a THz wave illuminates at the same time the sample (Homodyne/intensity detection).
- But we are interested on **HETERODYNE** detection (ie we want to recover both the amplitude and *PHASE* of the incoming THz or mm-wave). And this cannot be done with the usual photomixer approach.

Heterodyne detection: Optoelectronic Mixers



T. Yasui, S. Yokoyama, H. Inaba, K. Minoshima, T. Nagatsuma, and T. Araki, "Terahertz Frequency Metrology Based on Frequency Comb," IEEE J. Selected Topics in Quantum Electronics, vol. 17, pp. 191-201, (2011).

Heterodyne detection: Optoelectronic Mixers

- Optoelectronic mixers are typical schemes among Microwave Photonics techniques and are based on different configurations:
  - Use of external modulators
  - Dual-mode sources
  - Semiconductor Optical Amplifiers (SOAs)

Heterodyne detection: Optoelectronic Mixers

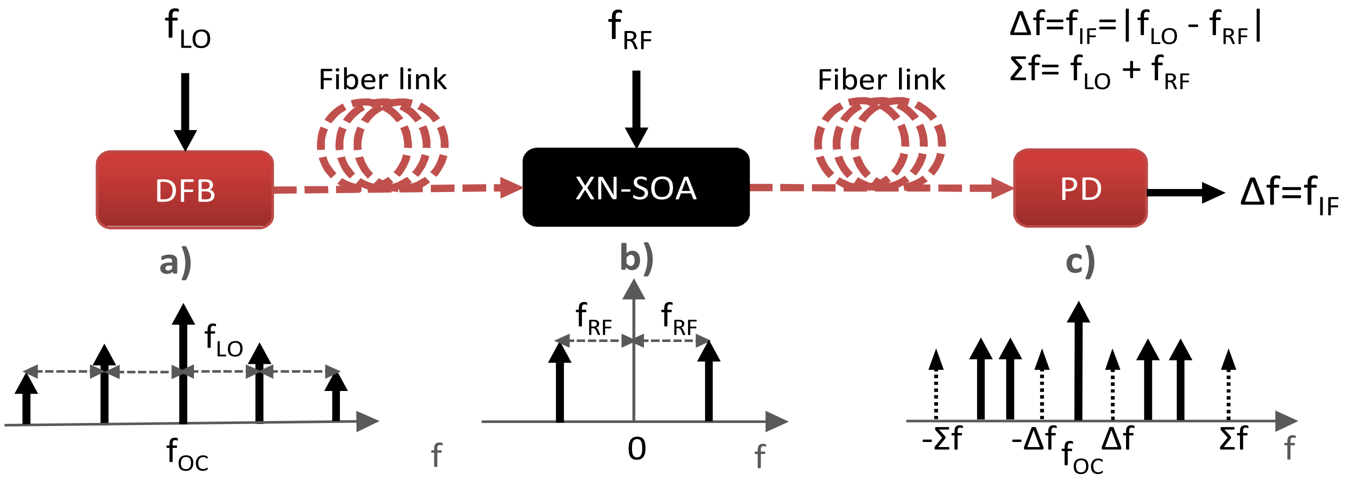
- Nevertheless these schemes are far from being a “true” photonic RF receiver as:
  - They usually need a complete RF front-end before the optoelectronic mixer is done.
  - The component count is high.
  - Associated sensitivity is typically low.
- New strategies are appearing.

“Figures of Merit” for mm-wave and THz signals Detectors

- Sensitivity/Noise
- Bandwidth (Broad Band)
- Dynamic Range

Heterodyne Systems!!

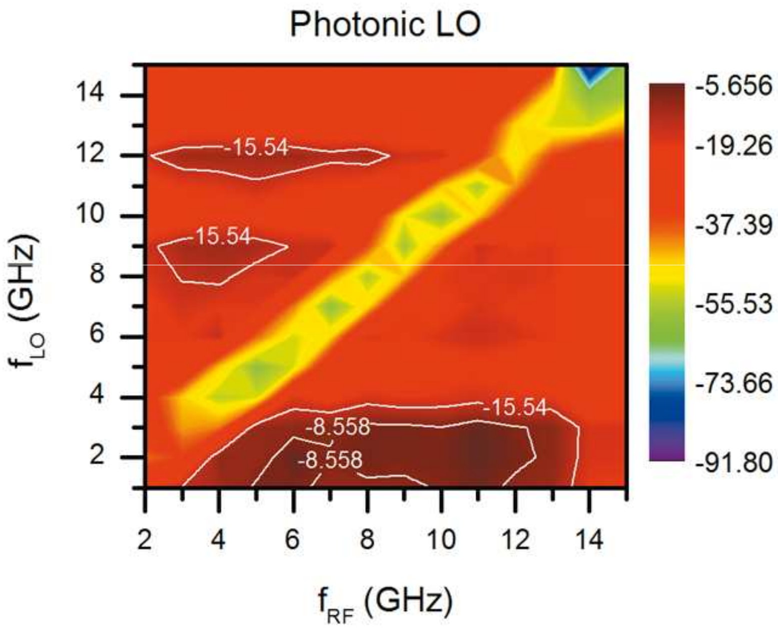
Heterodyne All-Optical pixel for RF detection based on XN-SOAs



This pixel can be combined with standard Local Oscillator and Intermediate Frequency Radio-over-Fiber distribution typical in Phased-array architectures.

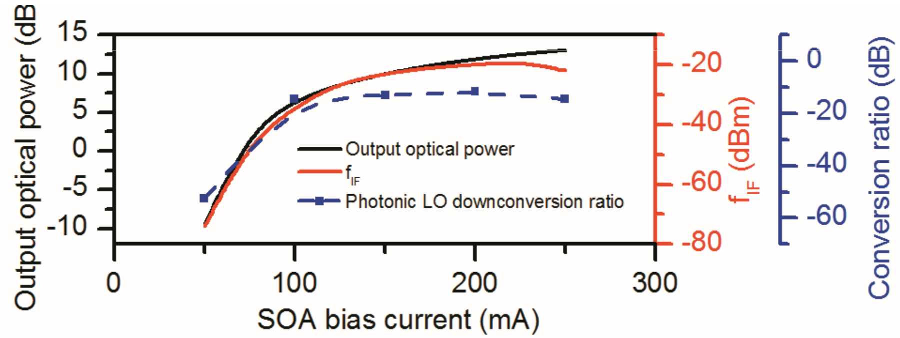
No need to provide the receiving pixel with RF LNA, only DC bias to the XN-SOA

Heterodyne All-Optical pixel for RF detection based on XN-SOAs



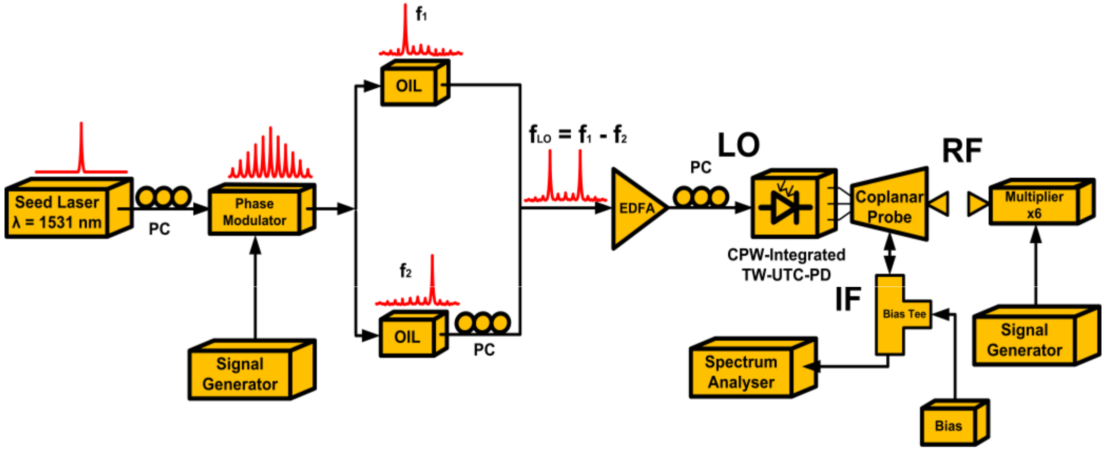
Downconversion ratio maps

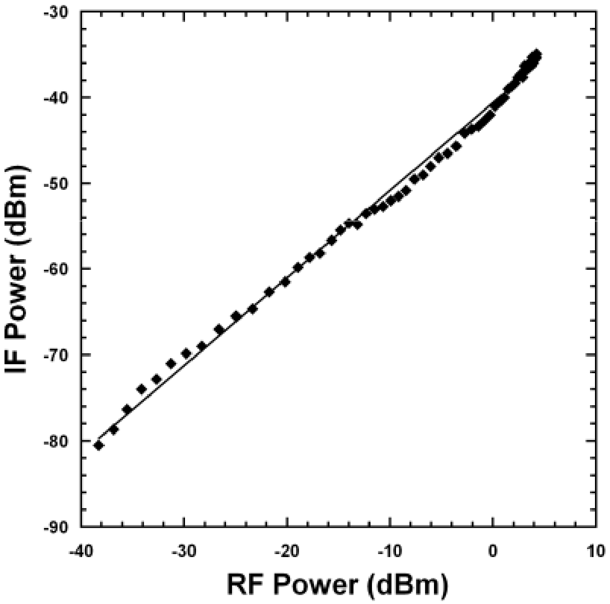
Evolution with SOA Current



A. R. Criado, C. de Dios, **P. Acedo** ‘Characterization of Ultra-Nonlinear SOA in a Heterodyne Detector Configuration With Remote Photonic Local Oscillator Distribution’ IEEE Photonics Technology Letters, vol.24, no.13, pp.1136-1138, (July 2012)

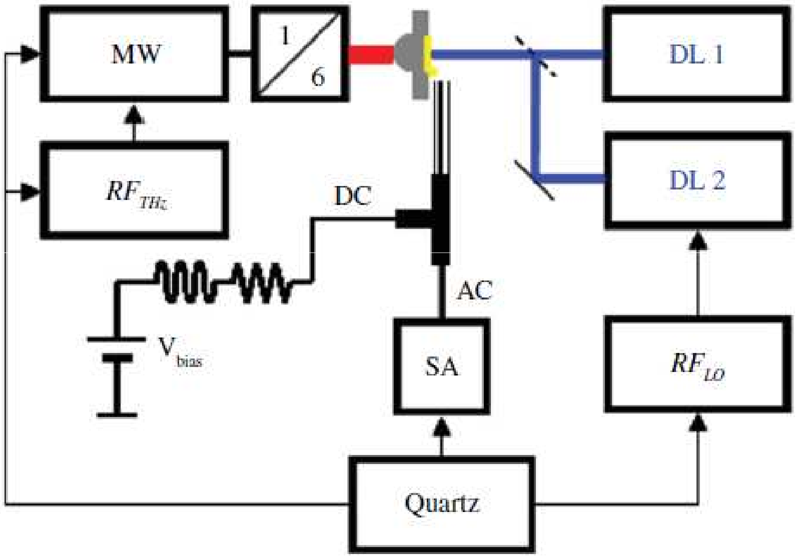
New Devices for Optoelectronic Heterodyne Detection: TW-UTC-PD

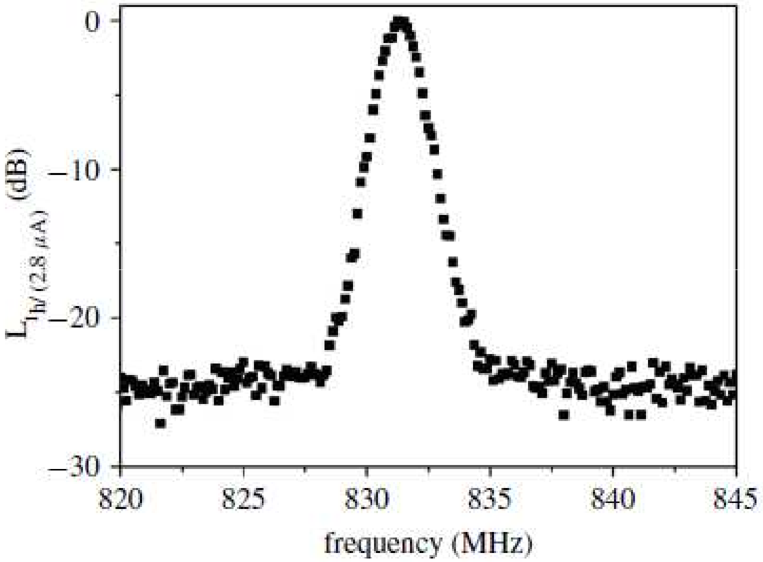




E. Rouvalis, M.J. Fice, C.C. Renaud and A. Seeds “Optoelectronic detection of millimeter-wave signals with travelling-wave uni-travelling carrier photodiodes” Optics Express, Vol. 19, Nº 3, pp. 2079-2084, 2011

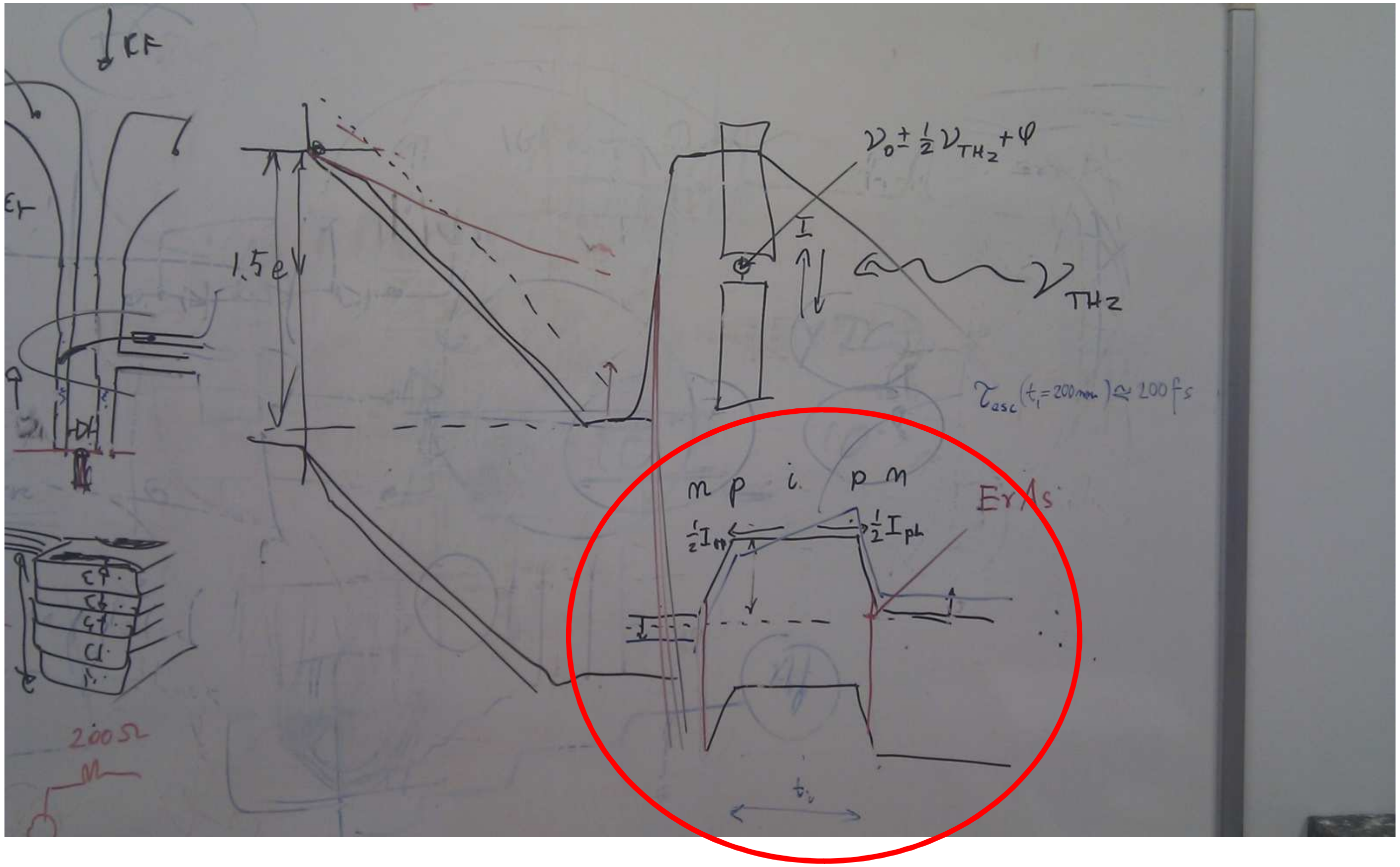
New Devices for Optoelectronic Heterodyne Detection: Photomixers





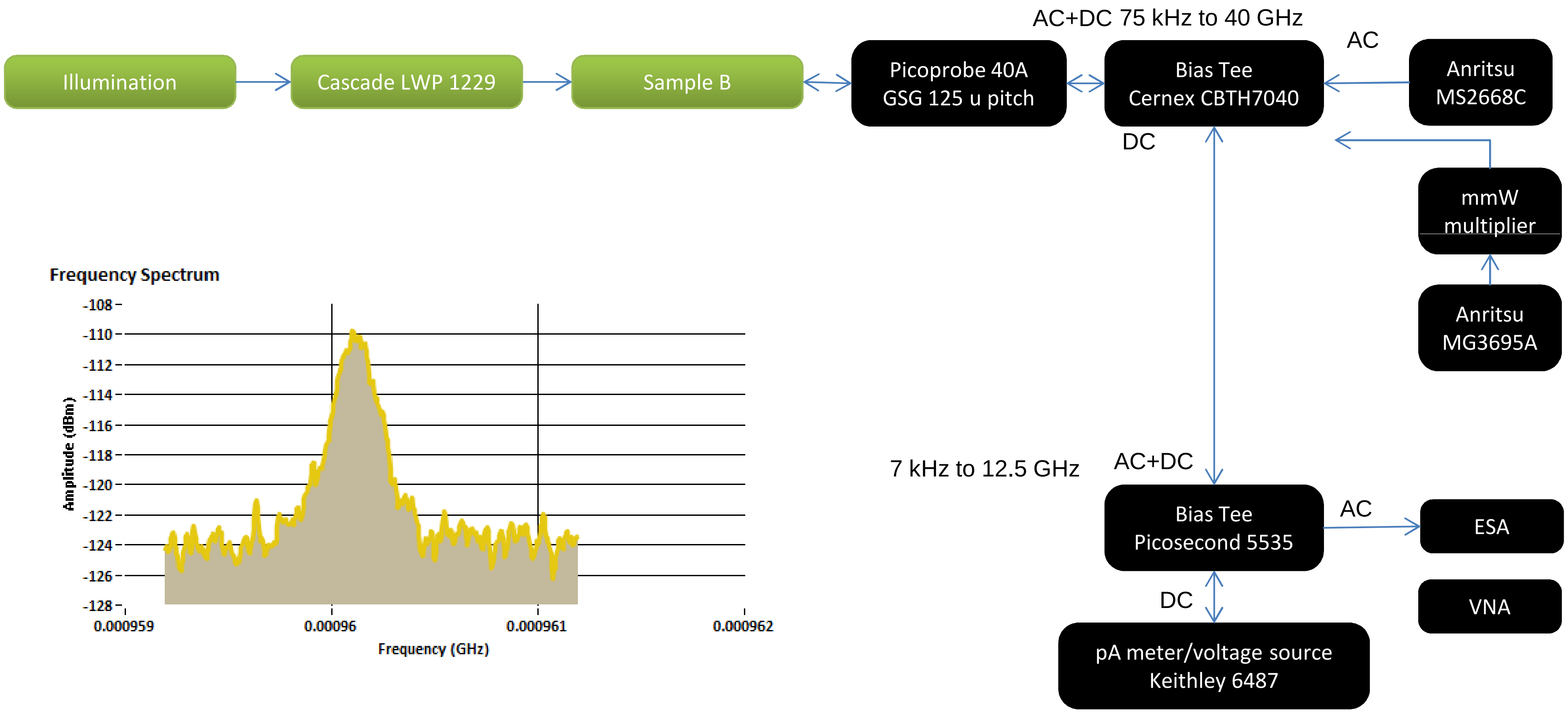
F.L. Constantin “Phase-coherent heterodyne detection in the Terahertz regime with a photomixer” IEEE Journal of Quantum Electronics, Vol. 47, Nº 11, pp. 1458-1462, 2011

New Devices for Optoelectronic Heterodyne Detection: ¿?



October 10th 2011

New Devices for Optoelectronic Heterodyne Detection: npipn



AC+DC 75 kHz to 40 GHz

Illumination

Cascade LWP 1229

Sample B

Picoprobe 40A
GSG 125 u pitch

Bias Tee
Cernex CBTH7040

AC

Anritsu
MS2668C

DC

mmW
multiplier

Anritsu
MG3695A

7 kHz to 12.5 GHz

AC+DC

Bias Tee
Picosecond 5535

AC

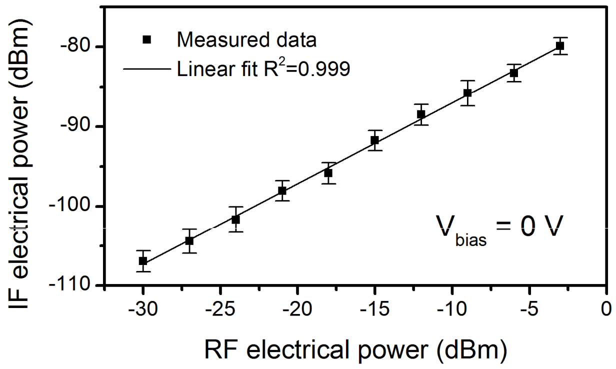
ESA

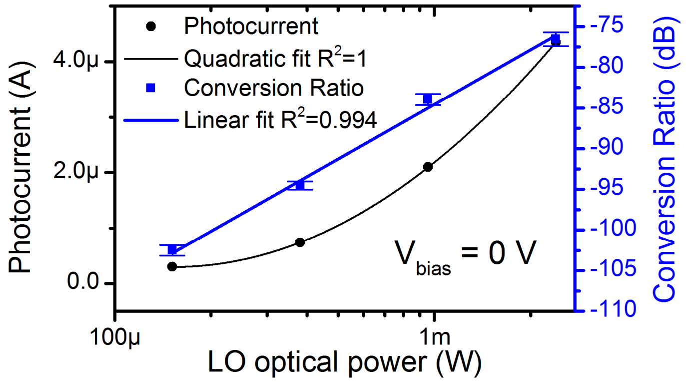
VNA

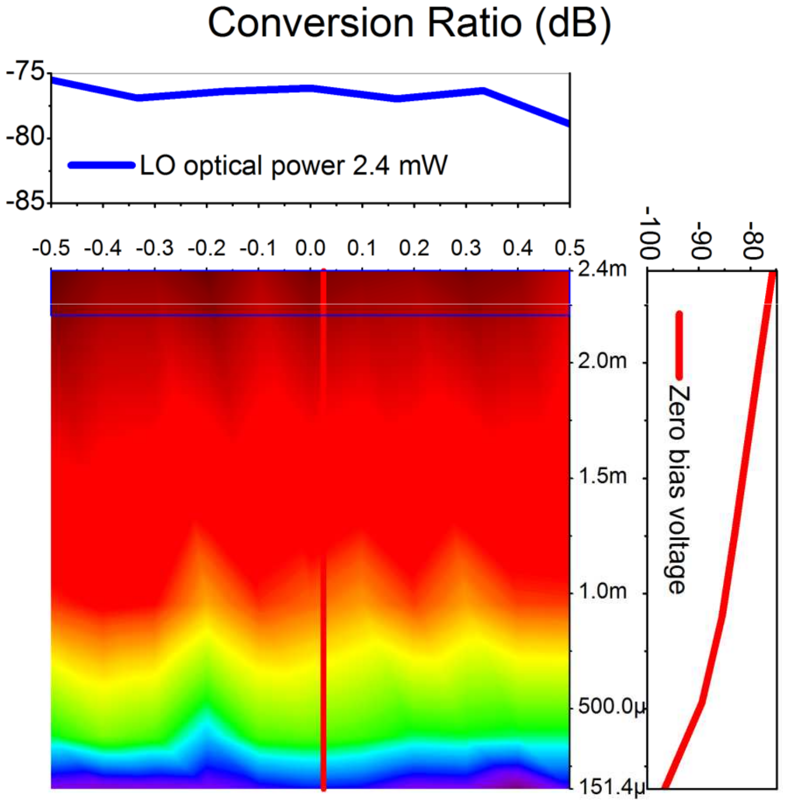
DC

pA meter/voltage source
Keithley 6487

New Devices for Optoelectronic Heterodyne Detection: npipn







Photonic Heterodyne Detection of mm-wave and THz Signals. Conclusions

- In the last years (2011/2012) novel schemes and components have appear that demonstrate the possibility of all-optical heterodyne receivers for mm-wave and THz signals.
- Such components can be easily integrated in current Radio-over-fiber Local oscillator distribution network typical to radars and electronic warfare systems for years now.
- Still a lot of work still ahead in the optimization of the described devices and schemes and other to come (superlattice nip-pin photomixers) to achieve the required sensitivity and, specially, dynamic range!!!

Conclusions (I)

- In order to really conquer the THz-gap we have to provide with low-cost, easy-to-operate, integrated components and transceivers that would act as “building blocks” for the systems that are to exploit the potentialities of this frequency band
- Photonics techniques based on the Synthesis of mm-wave and THz signals are becoming a reality in real-world applications for these frequency ranges associated firstly, to the high spectral quality of the generated signals and the integrations capacities (PICs); and secondly, to the great advantages associated to the use of telecommunications technology-based components and techniques.

Conclusions (II)

- Several strategies can be used for photonic synthesis (dual-mode structures, external modulators), but the use of OFCG along with selective filtering (either passive of OPLL based) provides with the best results in terms of spectral quality. Also continuous tunability has also been demonstrated
- Heterodyne detection using photonic techniques is also an active field of research. New schemes and devices have demonstrated all-optical receiving pixels in the mm-wave range (up to 100 GHz) that can take advantage of the current photonic LO and IF distribution architectures for radar and imaging radar developments.