Antenna Array Design Using Microwave Photonics Technology

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I gratefully acknowledge the support of:

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V. Hurm	IAF Freiburg

Microwave Photonics – Impact and Applications

Microwave photonics: (MWP)	Here: Coherent optical generation of radiation (temporally sinusoidal electric field) with frequencies from several GHz up to the THz-range

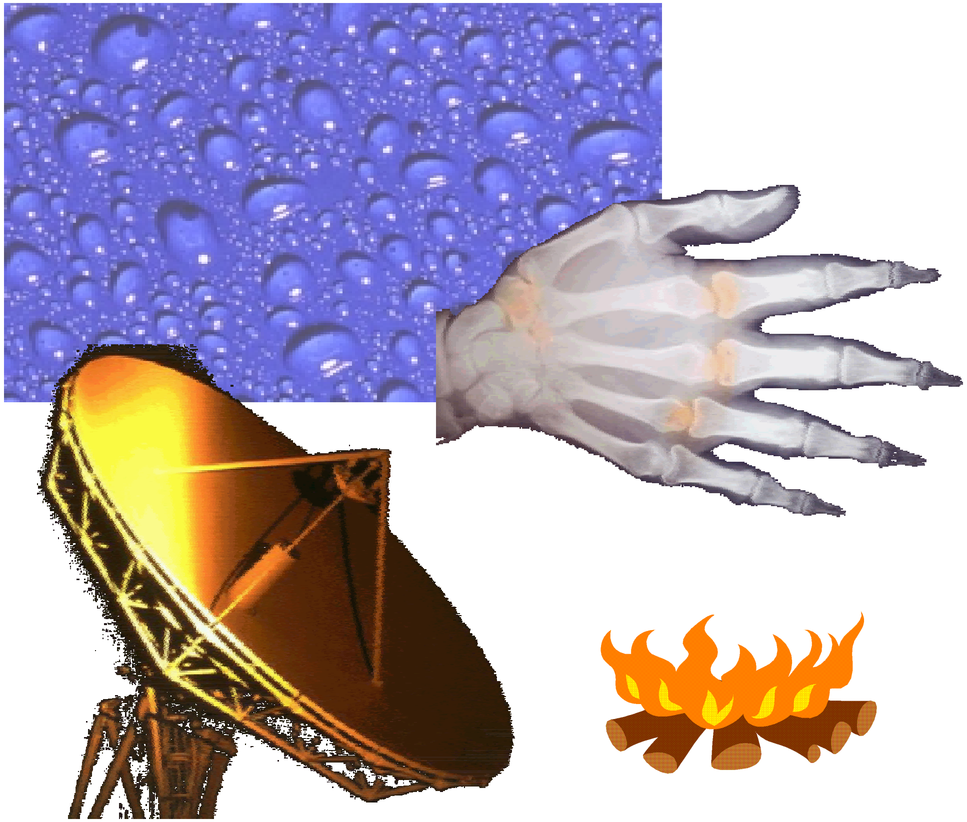
$2\ \text{GHz} \le f \le 60\ \text{GHz}$: **($15\ \text{cm} \ge \lambda \ge 5\ \text{mm}$)**	**Electronic generation of spectrally pure microwave signals, inexpensive distribution to many receivers via optical fibres, local demodulation, inexpensive electronic amplification**
Applications:	**Terrestrial communication (mobile phones, office, ”last mile”), radar, inter-satellite communication, sensors**

$60\ \text{GHz} \le f \le 100\ \text{GHz}$: **($5\ \text{mm} \ge \lambda \ge 3\ \text{mm}$)**	**Electronic signal generation more difficult, electronic amplifiers not yet standard products**
Applications:	**Radar, inter-satellite communication, sensors (distance)**

$100\ \text{GHz} \le f \le 10\ \text{THz}$: **($3\ \text{mm} \ge \lambda \ge 30\ \mu\text{m}$)**	**Electronic signal generation uneconomical or impossible, no electronic amplifiers available**
Applications:	**Radar, imaging, sensors, medical diagnostics**

A look into the future: Terahertz Photonics – What are T-rays?

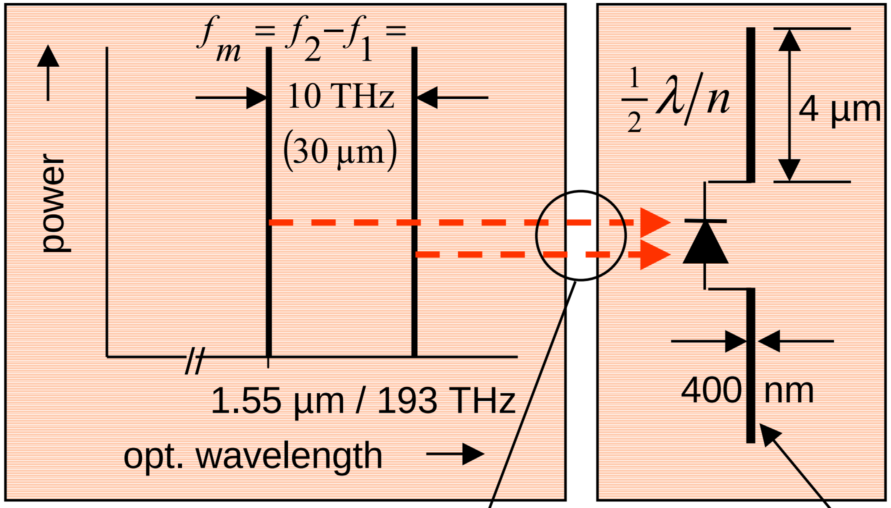
Quality control, medical diagnostics, gas spectroscopy



- Humidity (absorption lines 0.6 ... 2 THz, CLEO´98 CTuB5, Opt. Lett. 14 (1989) 1128): production of food
- Dermatology: Structure of burned skin without biopsy
- Tomography (Opt. Lett. 22 (1997) 904)
- T-rays replace Roentgen rays (X-rays):
  - Imaging of “invisible” objects
  - Inspection of pallets
  - Airport safety measures, drug detection
- Analysis of flames and gases (toxicity, Fourier spectrum)
- Quality control: Holes in plastic parts, plastics for car production
- Radar applications (measurement of reflection)

Terahertz Photonics – Generation of Coherent T-Rays

Mixing of two optical signals by a Schottky photodiode



fibre transmission

edge precision $1\% \cong 4\,\text{nm}$

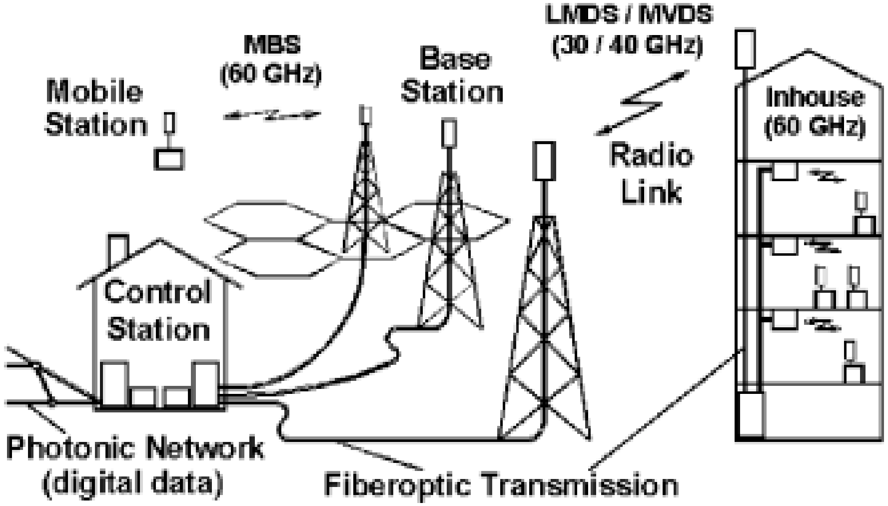
- **2 optical lines, difference frequency 10 THz**
- **Schottky diode as photodetector-mixer.**
  Lateral dimensions in 1-µm range
  (Light focus dimension $0.61 \cdot \lambda = 1$ µm)
  Junction capacitance $C \approx 3$ fF
  Series resistance $R \approx 5\,\Omega$ (!)
  ***RC* corner frequency $f_c \approx 11$ THz**
- **Integrated antenna, λ-dipole for 10 THz.**
  High edge precision in nm-range necessary
- **Receiving antenna with similar structure**
  as detector of T-rays

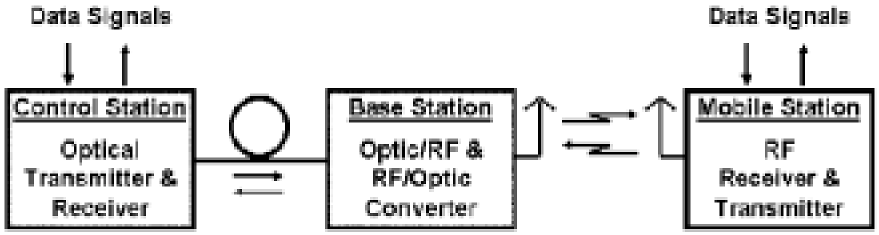
Technological Problems and Challenges

- **Electrochem. nano-structuring of Schottky PD: Substrate n-Si; metal (e.g. Pb); junction *C;* series *R***
- **Corrosion and passivation, accuracy, edge precision, and transmission line loss (type e.g. coplanar)**

Microwave Photonics – What Can Hybrid Techniques Do?

Micro and picocellular networks (HFR, Hybrid Fibre Radio)





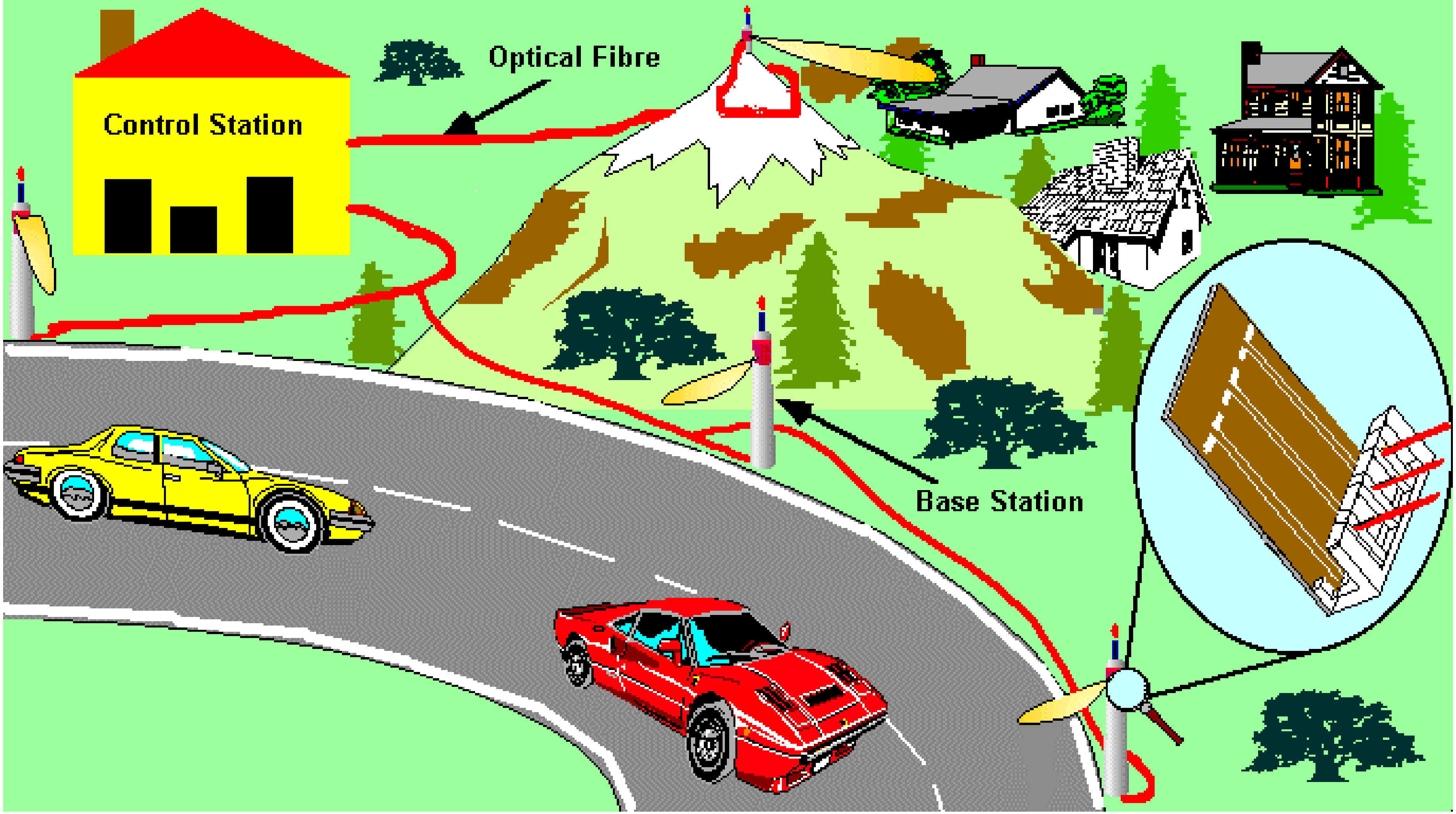
***Few* expensive *control stations* with frequency-stable microwave generators, *numerous* inexpensive *base stations* with opto-electronic converters and MMIC microwave amplifiers.**

- **Local Multipoint & Multipoint Video Distribution System (LMDS & MVDS)**
- **Mobile Broadband Systems (MBS)**
- **In-House, shop, and hangar systems**
- **Telematics, sensors, military and satellite communication**

Operation principle:

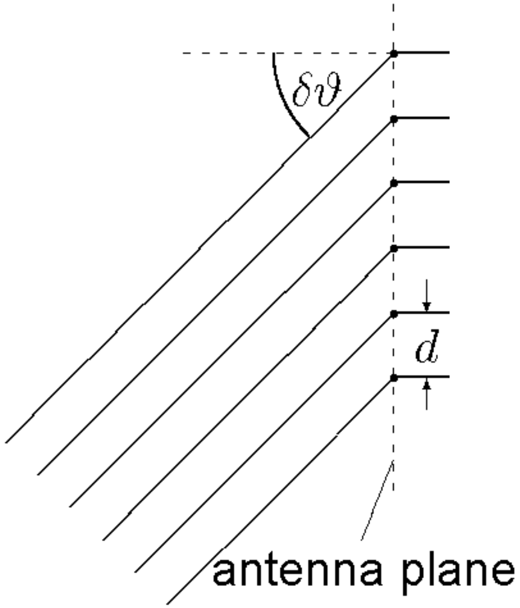
Data signals modulated on optical carrier, via low-loss fibre transmitted, in base station demodulated und radiated.

Example of HFR Control and Base Stations



Antenna Array, Beam Squint, and Beamforming Network (1)

Antenna array beam steering and squint



- **Problems with RF beamforming network (BFN):**
- **High losses, high dispersion, interference with microwave transm. lines and fields, bulky, complicated mechanical arrangement**

- **Antenna array modelled by linear array of point sources (•, \`grating´ constant d), $\delta\varphi = 0$**
- **Propagation in 1st diffraction order direction, tilted from normal $\vartheta = 90°$ by $\delta\vartheta$**
- **Well known diffraction formula** $\sin(\delta\vartheta) = \lambda_m / d$
- **With arbitrary $\delta\varphi$ at •, 0th order beam direction tilted by:**

$$\sin(\delta\vartheta) = \frac{\lambda_m}{d}\frac{\delta\varphi}{2\pi} = \frac{c}{\omega_m}\frac{\delta\varphi}{d}$$

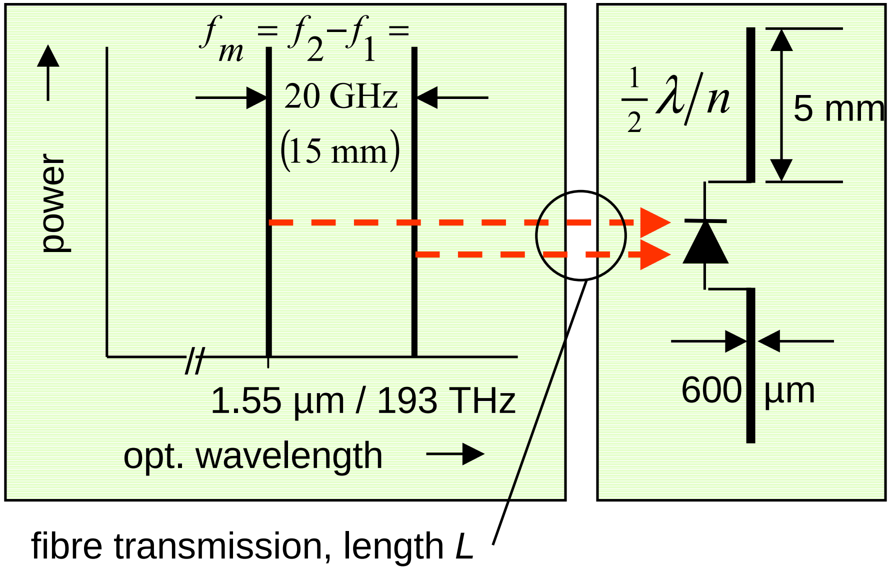
- **If subcarrier f_m varies with time t: beam squint $\delta\vartheta(t)$ for $\delta\varphi = \mathrm{const}_t$**
- **No squint even with wide bandwidth signal, if**

$$\delta\varphi \sim \omega_m$$

for all ω_m!

Antenna Array, Beam Squint, and Beamforming Network (2)

Recipe for RF transmission and optical beamforming network



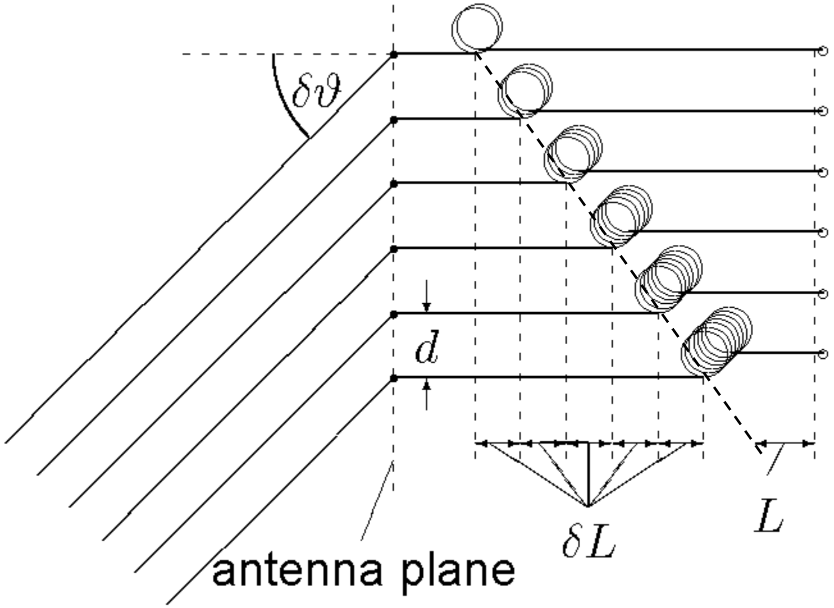
- **2 optical lines, difference frequency $f_m = 20\,\mathrm{GHz}$**
- **RF modulation signal transferred to one of the optical lines**
- **Transmit by optical single-mode fibre**
- **Detect original RF signal from optical carrier by mixing modulated and unmodulated line**
- **Mixing by detecting optical power with photodetector (quadratic demodulator, but no sum frequency!)**
- **Photocurrent contains the IF $f_m = f_2 - f_1$**
- **Amplify the photocurrent**
- **Radiate resulting signal by each antenna element**
- **Adjust the beamforming network by the lengths *L* of the optical fibres, either mechanically, or optically**

Beauties of optical TTD

- **Low volume, light, inexpensive**
- **Very low loss, very low dispersion**

Antenna Array, Beam Squint, and Beamforming Network (3)

Avoiding beam squint by TTD



- **Microwave photonics makes *optical* feeder network possible, greatly reduces problems of a true time delay (TTD) network:**
- **Low losses, low dispersion, not bulky, no interference with microw. transm. lines & fields**

TTD schematic (True Time Delay Network)

- **Linear array modelled by linear array of point sources •, fed at o with identical phases by delay lines of length $L_i = L + i\delta L$ with length increments δL**
- **RF current phase difference at • expressed by group delay time increment δt_g or, with group velocity v_g, by**

$$\delta\varphi = \omega_m \delta t_g = \omega_m \frac{\delta L}{v_g}$$

No beam squint

- **With arbitrary f_m and δL, 0th order beam direction tilted by**

$$\sin(\delta\vartheta) = \frac{\lambda_m}{d}\frac{\delta\varphi}{2\pi} = \frac{c}{\omega_m}\frac{\delta\varphi}{d} = \frac{c}{v_g}\frac{\delta L}{d}$$

RF Signal Fibre Transmission

Details of RF transmission over dispersive single-mode fibre

Transfer function of opt. transm. fibre, length L_i :

$$\breve{h}_i(f) = \exp\left[-\mathrm{j}\,\beta_i(\omega) L_i\right]$$

Feeds opt. receivers → RF drive of antenna elem.

Prop. const. β, group delay time $t_g / L = 5\,\mu\mathrm{s/km}$,

chromatic dispersion $C = 17\,\mathrm{ps}/(\mathrm{km\ nm})$:

$$\beta_\mathrm{i} \approx \beta(\omega_0) + (\omega - \omega_0)\frac{t_g}{L_i} - \frac{(\omega-\omega_0)^2}{2}\frac{\lambda_0^2}{2\pi c}C$$

Fibre length incr. @ RF mod. freq. $f_m = 20\,\mathrm{GHz}$:

$$\delta L_\mathrm{max} = \frac{v_g}{c}d = \frac{2}{3}\frac{\lambda_m}{2} = \frac{15}{3}\mathrm{mm} = 5\,\mathrm{mm}$$

Group delay time increment :

$$\delta t_{g\,\mathrm{max}} = \frac{\delta L_\mathrm{max}}{v_g} = \frac{d}{c} = \frac{\lambda_m}{2c} = \frac{1}{2 f_m} = 25\,\mathrm{ps}$$

Chrom. delay time err. for spectr. width $\Delta f = f_m$:

$$\Delta f = 20\,\mathrm{GHz},\ \ \Delta \ \ = \frac{(1.55\,\mu\mathrm{m})^2}{c}\Delta f = 0.16\,\mathrm{nm}$$

$$\delta t_{g\,C} = C\,\delta L_\mathrm{max}\Delta\lambda = 14\,\mathrm{fs} = 0.6\times 10^{-3}\,\delta t_{g\,\mathrm{max}}$$

Summary:

Chromatic dispersion unimportant for OBFN

Fibre output spectrum from transfer function :

$$\breve{a}_L(f) = \breve{h}(f)\left[\delta(f - f_1) + \delta(f - f_2)\right]$$

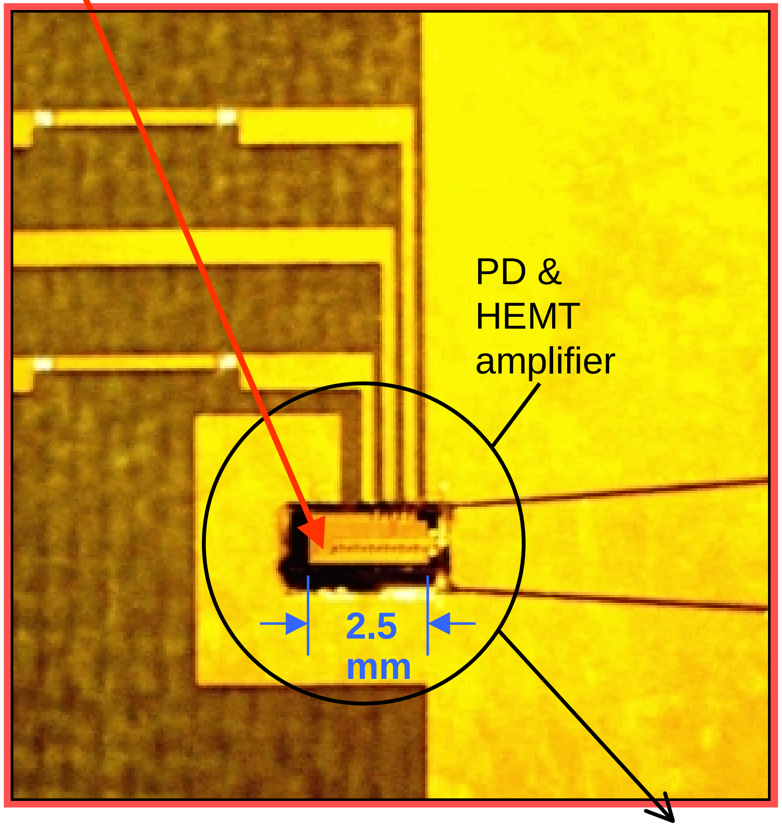
PD detects opt. power (quadr. demodul. for f_m,

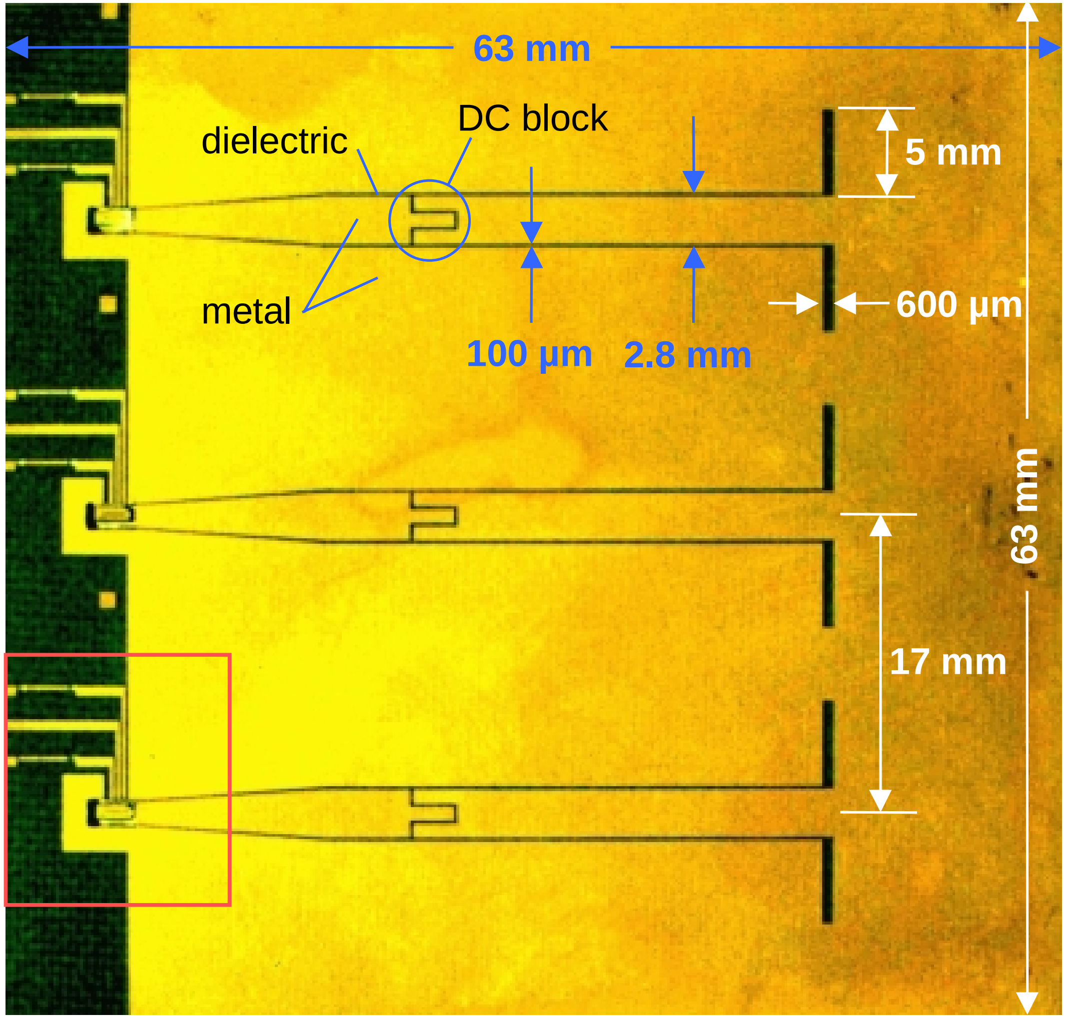
no optical sum frequency!), RF current *i(t)* **:**

$$i(t) \propto \left\langle \left| F^{-1}\left\{ \breve{a}_L(f) \right\} \right|^2 \right\rangle \propto \cos(\omega_m t - \underset{\varphi_i \propto \omega_m L_i}{\omega_m t_g})$$

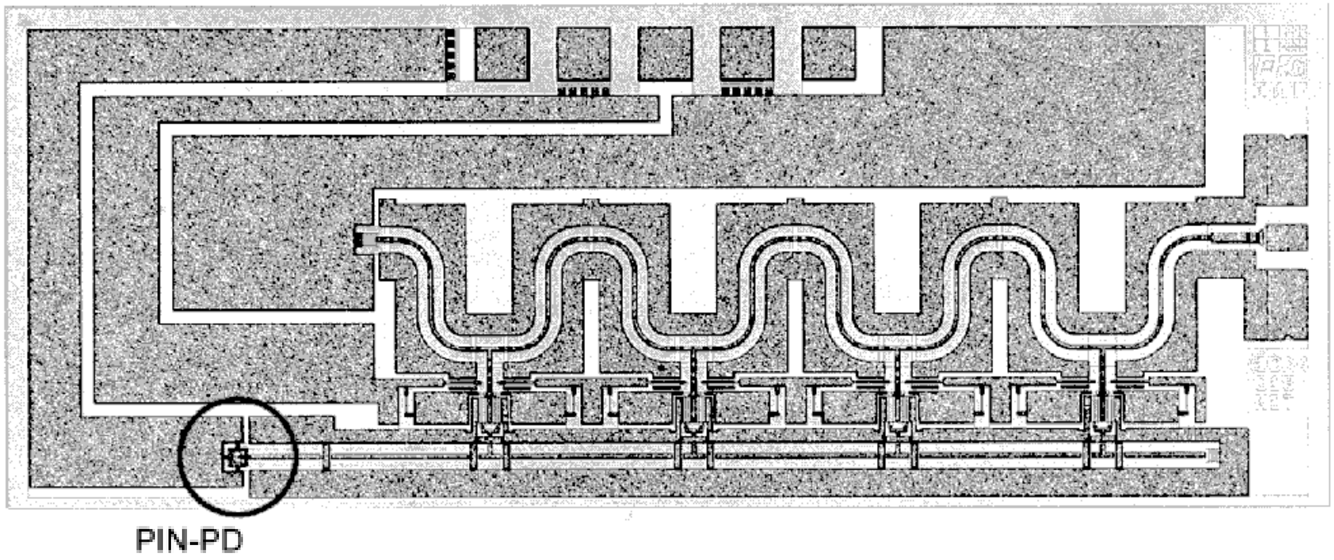
λ-Dipole Antenna with Optical Feeder at 20 GHz

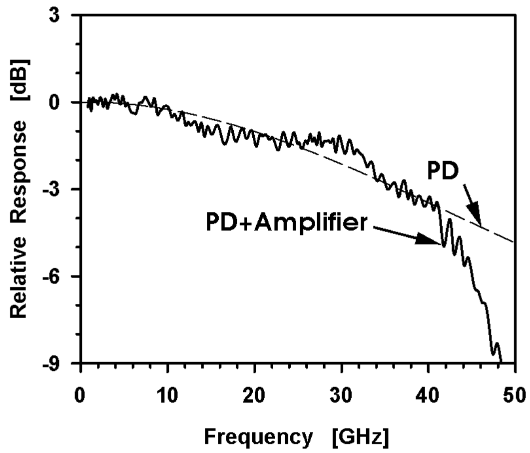
Each of 3 antenna elements separately fed via single-mode glass fibre, which illuminates PD from top.

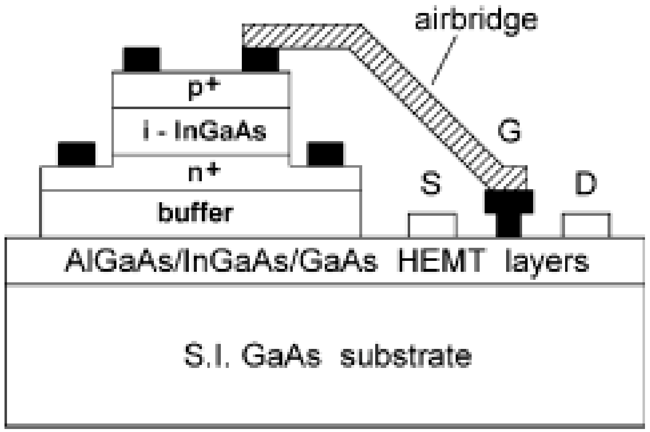




HEMT Photoreceiver (IAF, Hurm et al. ECOC 1998)



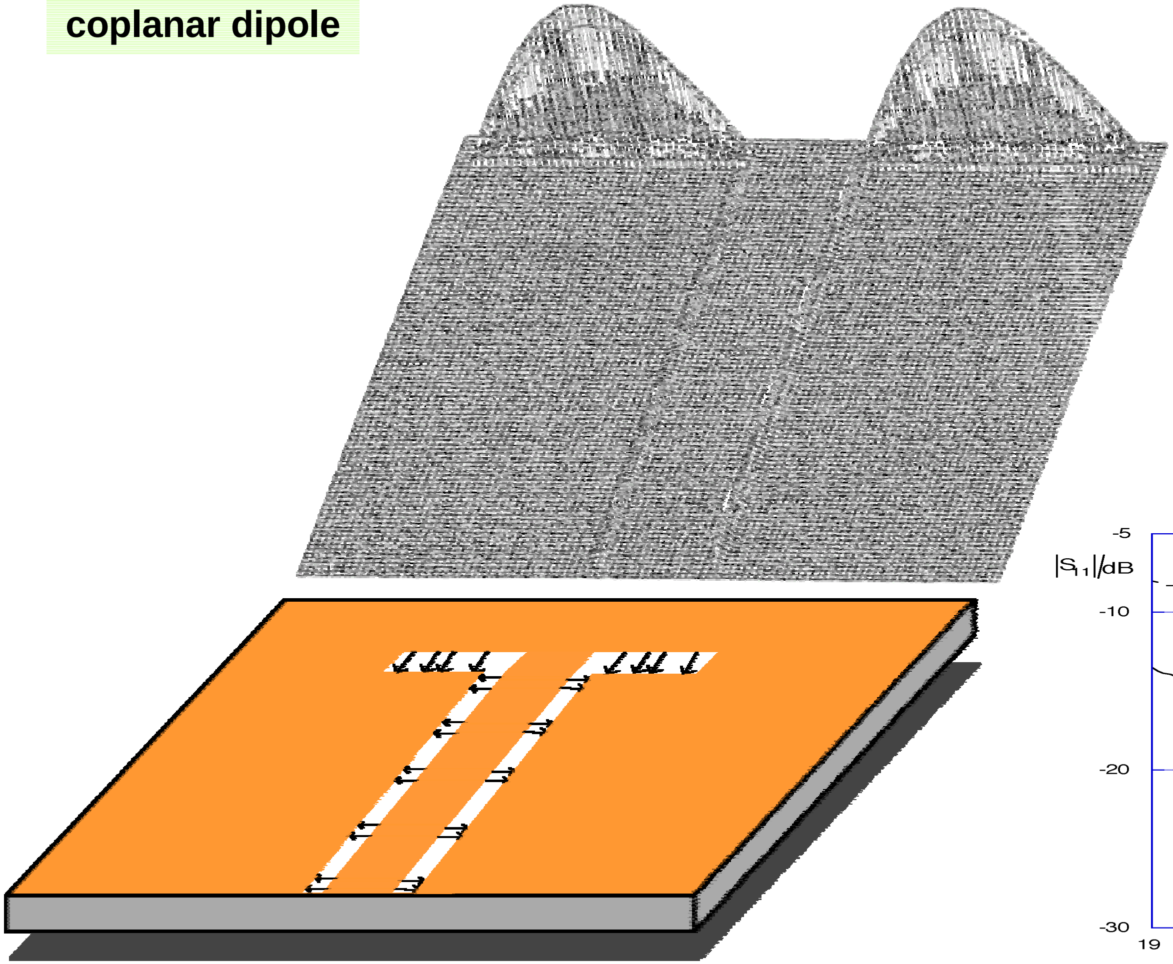




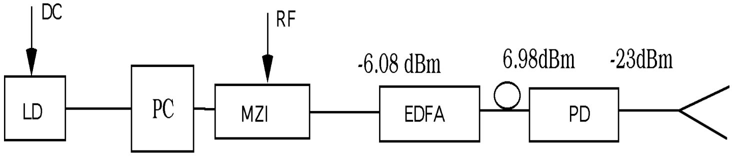
- **OEIC on semi-insulating GaAs (2.5 mm × 1 mm)**
- **PD 10 µm∅, 3-dB bandw. 36.5 GHz @ 25 Ω, RC limited (- - -)**
- **Distributed amplifier with 4 HEMT stages**
- **Cascoded pseudomorphic HEMT**
  Gate length 150 nm, InGaAs channel 12 nm
  Transconductance g_m = 754 mS / mm, current-gain cut-off frequency f_T = 90 GHz,
  Maximum oscillation frequency f_{max} = 150 GHz
  Coplanar 50- Ω output

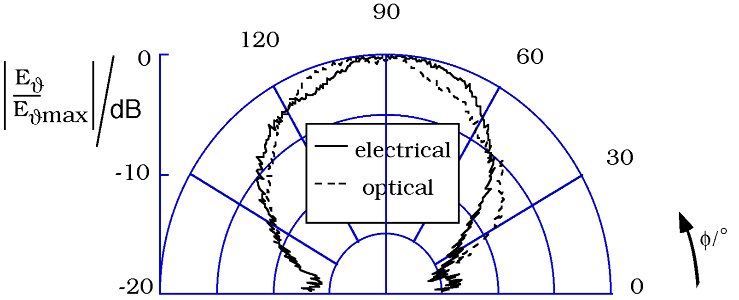
Coplanar λ-dipole at 20 GHz

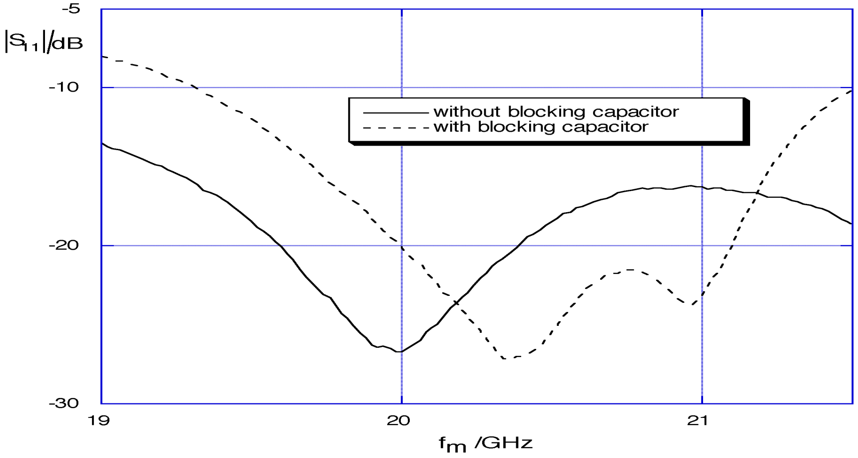
Electric field at coplanar dipole



Radiation pattern and input impedance







Summary and Outlook

Present state

Microwave photonics

Future work

- **Data transmitted to base stations via photonic networks**
- **Application of MWP (here: at 20 GHz) mainly for *radio communication and sensors***
- **Mass market for bridging the “last mile” for connecting subscribers to *broadband communication networks* without road works**
- **With optical beamforming networks, the radiation patterns don’t show *”beam squint“***
- **Length reconfiguration of fibre feeders for *spatial beam tracking***

- **Upgrade of model system from 20 GHz to higher frequencies, e.g., 40 GHz**
- **Design and test of optical beamforming networks**
- **Antenna design for semiconductor substrates with refractive indices near n = 3,6**
- **Problems: Radiation efficiency**
  Amplifier heat removal

Future Terahertz Photonics

- **Design of THz transm. lines with edge precision in the 4-nm region on semicond. substrates; losses**
- **Design and investigation of photo-sensitive Schottky diodes**
- **Antenna design**